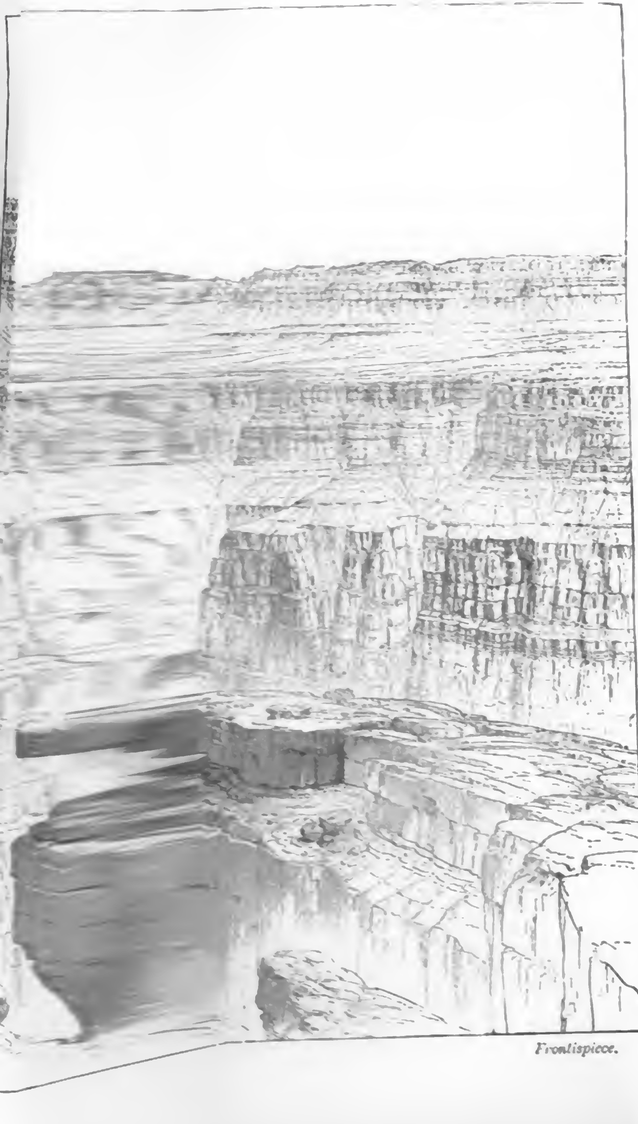
Textbook of geology

Sir Archibald Geikie



Frontispiece.

TEXT-BOOK OF GEOLOGY.

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PREFACE.

THE method of treatment adopted in this Text-Book is one which, while conducting the class of Geology in the University of Edinburgh, I have found to afford the student a good grasp of the general principles of the science, and at the same time a familiarity with and interest in details of which he is enabled to see the bearing in the general system of knowledge. A portion of the volume appeared in the autumn of 1879 as the article "Geology" in the *Encyclopædia Britannica.* My leisure since that date has been chiefly devoted to expanding those sections of the treatise which could not be adequately developed in the pages of a general work of reference.

While the book will not, I hope, repel the general reader who cares to know somewhat in detail the facts and principles of one of the most fascinating branches of natural history, it is intended primarily for students, and is therefore adapted specially for their use. The digest given of each subject will be found to be accompanied by references to memoirs where a fuller statement may be sought. It has long been a charge against the geologists of Great Britain that, like their countrymen in general, they are apt to be somewhat insular in their conceptions, even in regard to their own branch of science.[1] Of course, specialists who have devoted themselves to the investigation of certain geological formations or of a certain group of fossil animals, have made themselves familiar with what has been written upon their subject in other countries. But I am afraid there is still not a little truth in the charge, that the general body of geologists here is but vaguely acquainted with geological types and illustrations other than such as have been drawn from the area of the British Isles. More particularly is the accusation true in regard to American geology. Comparatively few of us have any adequate conception of the simplicity and grandeur of the examples by which the principles of the science have been enforced on the other side of the Atlantic.

Fully sensible of this natural tendency, I have tried to keep it in constant view as a danger to be avoided as far as the conditions of my task would allow. In a text-book designed for use in Britain the illustrations must obviously be in the first place British. A truth can be enforced much more vividly by an example culled from familiar ground than by one taken from a distance. But I have striven to widen the vision of the student by indicating to him that while the

[1] See, for instance, K. C. von Leonhard, who, in his *Basalt-Gebilde* (1832), says:—"Ein Tadel, welcher viele geognostische Schriftsteller Englands nicht ungerecht trifft, ist ihre Unbekanntschaft mit der Litteratur des Auslandes; sie eignen sich das Gute fremder Nationen zu wenig an. Auch kommt ihnen unnöthige Umständlichkeit und ermüdende Weitschweifigkeit und eine Art gewissenhafter Peinlichkeit nicht selten zu Schulden, so dass manche ihrer Bücher sehr lesenswürdig, aber nicht besonders lesbar sind."—Vol. i. p. 40.

general principles of the science remain uniform, they receive sometimes a clearer, sometimes a somewhat different, light from the rocks of other countries than our own. If from these references he is induced to turn to the labours of our fellow-workers on the Continent, and to share my respect and admiration for them, a large part of my design will have been accomplished. If, further, he is led to study with interest the work of our brethren across the Atlantic, and to join in my hearty regard for it and for them, another important section of my task will have been fulfilled. And if in perusing these pages he should find in them any stimulus to explore nature for himself, to wander with the enthusiasm of a true geologist over the length and breadth of his own country, and, where opportunity offers, to extend his experience and widen his sympathies by exploring the rocks of other lands, the remaining and chief part of my aim would be attained.

Geology is so progressive a science, and the amount of literature devoted to its illustration is so constantly increasing, that in a work of such proportions as the present it must necessarily happen that between the printing off of the earlier portions and the final publication of the book, memoirs appear which the author regretfully finds himself precluded from using as he would gladly have done had they been earlier available. As examples in the present instance, I may refer to Mr. Darwin's 'Vegetable Mould,' Mr. Fisher's 'Physics of the Earth's Crust,' Mr. Judd's 'Volcanoes,' Dr. Tietze's 'Memoir on Lemberg' (*Jahrb. K.K. Geolog. Reichsanst.* xxxii. 1882), and Mr. Reusch's paper on 'Upper Silurian Fossils among the Metamorphic Rocks of Bergen' (Christiania, *Universitetsprogram.* 1882).

The illustrations of Fossils in Book VI. have been chiefly drawn by Mr. George Sharman; a few by Mr. B. N. Peach, and one or two by Dr. R. H. Traquair, F.R.S., to all of whom my best thanks are due. The publishers having become possessed of the wood-blocks of Sir Henry De la Beche's 'Geological Observer,' I gladly made use of them as far as they could be employed in Books III. and IV. Sir Henry's sketches were always both clear and artistic, and I hope that students will not be sorry to see some of them revived. They are indicated by the letter (B). The engravings of the microscopic structure of rocks are from my own drawings, and I have also availed myself of materials from my sketch-books. The frontispiece is a reduction of a drawing by Mr. W. H. Holmes, whose pictures of the scenery in the Far West of the United States are by far the most remarkable examples yet attained of the union of artistic effectiveness with almost diagrammatic geological distinctness and accuracy. Captain Dutton, of the Geological Survey of the United States, furnished me with this drawing and also requested Mr. Holmes to make for me the cañon-sections given in Book VII. To both of these kind friends I desire to acknowledge my indebtedness.

28, Jermyn Street, London,
12*th June*, 1882.

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GEOLOGY.

INTRODUCTION.

GEOLOGY is the science which investigates the history of the Earth. Its object is to trace the progress of our planet from the earliest beginnings of its separate existence, through its various stages of growth, down to the present condition of things. It unravels the complicated processes by which each continent has been built up, and traces the vast geographical revolutions of which each has been the site. While seeking to determine the order of the evolution of the earth's great surface-features, it likewise follows, even into detail, the varied sculpture of mountain and valley, crag and ravine.

Nor does this science confine itself merely to changes in the inorganic world. Geology shows that the present races of plants and animals are the descendants of other and very different races which once peopled the earth. It teaches that there has been a progress of the inhabitants, as well as one of the globe on which they have dwelt; that each successive period in the earth's history, since the introduction of living things, has been marked by characteristic types of the animal and vegetable kingdoms; and that, how imperfectly soever they may have been preserved or may be deciphered, materials exist for a history of life upon the planet. The geographical distribution of existing faunas and floras is often made clear and intelligible by geological evidence; and in the same way light is thrown upon some of the remoter phases in the history of man himself.

A subject so comprehensive as this must require a wide and varied basis of evidence. One of the characteristics of geology is to gather evidence from sources which at first sight seem far removed from its scope, and to seek aid from almost every other leading branch of science. Thus, in dealing with the earliest conditions of the planet, the geologist must fully avail himself of the labours of the astronomer. Whatever is ascertainable by telescope, spectroscope, or chemical analysis, regarding the constitution of other heavenly bodies, has a geological bearing. The experiments of the physicist, undertaken to determine conditions of matter and of energy, may sometimes be taken as the starting-points of geological investigation. The work of the chemical laboratory forms the foundation of a vast and increasing mass of geological inquiry. To

the botanist, the zoologist, even to the unscientific, if observant, traveller by land or sea, the geologist turns for information and assistance.

But while thus culling freely from the dominions of other sciences, geology claims as its peculiar territory the rocky framework of the globe. In the materials composing that framework, their composition and arrangement, the processes of their formation, the changes which they have individually undergone, and the grand terrestrial revolutions to which they bear witness, lie the main data of geological history. It is the task of the geologist to group these elements in such a way that they may be made to yield up their evidence as to the march of events in the evolution of the planet. He finds that they have in large measure arranged themselves in chronological sequence,—the oldest lying at the bottom and the newest at the top. Relics of an ancient sea-floor are overlaid with traces of a vanished land-surface; these are in turn covered by the deposits of a former lake, above which once more appear proofs of the return of the sea. Among these rocky records lie the lavas and ashes of long-extinct volcanoes. The ripple left upon the shore, the cracks formed by the sun's heat upon the muddy bottom of a dried-up pool, the very imprint of the drops of a passing rain-shower, have all been accurately preserved, and often bear witness to geographical conditions widely different from those that exist where such markings are now found.

But it is mainly by the remains of plants and animals imbedded in the rocks that the geologist is guided in unravelling the chronological succession of geological changes. He has found that a certain order of appearance characterises these organic remains; that each great group of rocks is marked by its own special types of life; that these types can be recognised, and that the rocks in which they occur can be correlated, even in distant countries, where no other means of comparison is available. At one moment he has to deal with the bones of some large mammal scattered through a deposit of superficial gravel, at another time with the minute foraminifers and ostracods of an upraised sea-bottom. Corals and crinoids crowded and crushed into a massive limestone on the spot where they lived and died, ferns and terrestrial plants matted together into a bed of coal where they originally grew, the scattered shells of a submarine sand-bank, the snails and lizards that left their mouldering remains within a hollow tree, the insects that have been imprisoned within the exuding resin of old forests, the footprints of birds and quadrupeds or the trails of worms left upon former shores—these, and innumerable other pieces of evidence, enable the geologist to realise in some measure what the vegetable and animal life of successive periods has been, and what geographical changes the site of every land has undergone.

It is evident that to deal successfully with these varied materials, a considerable acquaintance with different branches of science is

desirable. The fuller and more accurate the knowledge which the geologist has of kindred branches of inquiry, the more interesting and fruitful will be his own researches. From its very nature geology demands on the part of its votaries wide sympathy with investigation in almost every branch of natural science. Especially necessary is a tolerably large acquaintance with the processes now at work in changing the surface of the earth, and of at least those forms of plant and animal life whose remains are apt to be preserved in geological deposits, or which in their structure and habitat enable us to realise what their forerunners were.

It has often been insisted upon that the present is the key to the past; and in a wide sense this assertion is eminently true. Only in proportion as we understand the present, where everything is open on all sides to the fullest investigation, can we expect to decipher the past, where so much is obscure, imperfectly preserved, or not preserved at all. A study of the existing economy of nature ought evidently to be the foundation of the geologist's training.

While, however, the present condition of things is thus employed, we must obviously be on our guard against the danger of unconsciously assuming that the phase of nature's operations which we now witness has been the same in all past time; that geological changes have taken place in former ages in the manner and on the scale which we behold to-day, and that at the present time all the great geological processes, which have produced changes in the past eras of the earth's history, are still existent and active. Of course we may assume this uniformity of action, and use the assumption as a working hypothesis. But it ought not to be allowed any firmer footing, nor on any account be suffered to blind us to the obvious truth that the few centuries wherein man has been observing nature form much too brief an interval, by which to measure the intensity of geological action in all past time. For aught we can tell the present is an era of quietude and slow change, compared with some of the eras that have preceded it. Nor can we be sure that, when we have explored every geological process now in progress, we have exhausted all the causes of change which, even in comparatively recent times, have been at work.

In dealing with the Geological Record, as the accessible solid part of the globe is called, we cannot too vividly realise that at the best it forms but an imperfect chronicle. Geological history cannot be compiled from a full and continuous series of documents. Owing to the very nature of its origin the record is necessarily from the first fragmentary, and it has been further mutilated and obscured by the revolutions of successive ages. And even where the chronicle of events is continuous, it is of very unequal value in different places. In one case, for example, it may present us with an unbroken succession of deposits many thousands of feet in thickness, from which, however, only a few meagre facts as to geological history can be gleaned. In another instance it brings before us, within the compass

of a few yards, the evidence of a most varied and complicated series of changes in physical geography, as well as an abundant and interesting suite of organic remains. These and other characteristics of the geological record will become more apparent and intelligible to the student as he proceeds in the study of the science.

In the present volume the subject will be distributed under the following leading divisions.

1. *The Cosmical Aspects of Geology.*—It is desirable to realise some of the more important relations of the earth to the other members of the solar system, of which it forms a part, seeing that geological phenomena are largely the result of these relations. The form and motions of the planet should be briefly touched upon, and attention should be directed to the way in which these planetary movements influence geological change. The light cast upon the early history of the earth by researches into the composition of the sun and stars deserves notice here.

2. *Geognosy,—an Inquiry into the Materials of the Earth's Substance.*—This division describes the constituent parts of the earth, its envelopes of air and water, its solid crust, and the probable condition of its interior. Especially, it directs attention to the more important minerals of the crust, and the chief rocks of which that crust is built up. In this way it lays a foundation of knowledge regarding the nature of the materials constituting the mass of the globe, from which we may next proceed to investigate the processes by which these materials are produced and altered.

3. *Dynamical Geology* embraces an investigation of the operations which lead to the formation, alteration, and disturbance of rocks. It considers the nature and operation of the processes that have determined the distribution of sea and land, and have moulded the forms of the terrestrial ridges and depressions. It further investigates the changes which are in progress over the surface of the land, whether these are due to subterranean disturbance, or to the effect of operations above ground. Such an inquiry necessitates a careful study of the existing geological economy of nature, and forms a fitting introduction to the investigation of the geological changes of former periods. This and the previous section, including most of what is embraced under Physical Geography and Petrogeny or Geogeny, will here be discussed more in detail than is usual in geological treatises.

4. *Geotectonic, or Structural Geology—the Architecture of the Earth.*—This section of the investigation discusses the mode of arrangement of the various materials composing the crust of the earth. It proves that some have been formed in beds or strata, whether by the deposit of sediment on the floor of the sea, or by the slow aggregation of organic forms, that others have been poured out from subterranean sources in sheets of molten rock, or in showers of loose dust, which have been built up into mountains and plateaux. It further shows that rocks originally laid down in almost horizontal

beds have subsequently been crumpled, contorted, dislocated, invaded by igneous masses from below, and rendered sometimes intensely crystalline. It teaches, too, that wherever exposed above sea-level they have been incessantly worn down, and have often been depressed, so that older came to be buried beneath later accumulations.

5. *Palæontological Geology.*—This branch of the subject deals with the organic forms which are found preserved in the rocks of the crust of the earth. It includes such questions as the relations between extinct and living types, the laws which appear to have governed the distribution of life in time and in space, the value of fossils and the relative importance of different genera of animals and plants in geological inquiry, and the nature and use of the evidence from organic remains regarding former conditions of physical geography.

6. *Stratigraphical Geology.*—This section might be called geological history. It works out the chronological succession of the great formations of the earth's crust, and endeavours to trace the sequence of events of which they contain the record. More particularly it determines the order of succession of the various plants and animals which in past time have peopled the earth, and thus ascertains what has been the grand march of life upon the planet.

7. *Physiographical Geology,* starting from the basis of fact laid down by stratigraphical geology regarding former geographical changes, embraces an inquiry into the history of the present features of the earth's surface—continental ridges and ocean basins, plains, valleys, and mountains. It investigates the structure of mountains and valleys, compares the mountains of different countries and ascertains the relative geological dates of their upheaval. It explains the causes on which local differences of scenery depend, and shows under what very different circumstances, and at what widely separated intervals, the varied contours, even of a single country, have been produced.

BOOK I.

COSMICAL ASPECTS OF GEOLOGY.

Before geology had attained to the position of an inductive science, it was customary to begin all investigations into the history of the earth by propounding or adopting some more or less fanciful hypothesis in explanation of the origin of our planet, or of the universe. Such preliminary notions were looked upon as essential to a right understanding of the manner in which the materials of the globe had been put together. To the illustrious James Hutton (1785) geologists are indebted for strenuously upholding the doctrine that it is no part of the province of geology to discuss the origin of things. He taught them that in the materials from which geological evidence is to be compiled there can be found "no traces of a beginning, no prospect of an end." In England, mainly to the influence of the school which he founded, and to the subsequent rise of the Geological Society (1807), which resolved to collect facts instead of fighting over hypotheses, is due the disappearance of the crude and unscientific cosmologies of previous centuries.

But there can now be little doubt that in the reaction against those visionary and often grotesque speculations, geologists were carried too far in an opposite direction. In allowing themselves to believe that geology had nothing to do with questions of cosmogony, they gradually grew up in the conviction that such questions could never be other then mere speculation, interesting or amusing as a theme for the employment of the fancy, but hardly coming within the domain of sober and inductive science. Nor would they soon have been awakened out of this belief by anything in their own science. It is still true that in the data with which they are accustomed to deal, as comprising the sum of geological evidence, there can be found no trace of a beginning, though there is ample proof of constant, upward progression from some invisible starting-point. The oldest rocks which have been discovered on any part of the globe have probably been derived from other rocks older than themselves. Geology by itself has not yet revealed, and is little likely ever to reveal, a portion of the first solid crust of our globe. If then

geological history is to be compiled from direct evidence furnished by the rocks of the earth, it cannot begin at the beginning of things, but must be content to date its first chapter from the earliest period of which any record has been preserved among the rocks.

Nevertheless, though geology in its usual restricted sense has been, and must ever be, unable to reveal the earliest history of our planet, it no longer ignores, as mere speculation, what is attempted in this subject by its sister sciences. Astronomy, physics, and chemistry have in late years all contributed to cast much light on the earlier stages of the earth's existence, previous to the beginning of what is commonly regarded as geological history. Whatever extends our knowledge of the former conditions of our globe may be legitimately claimed as part of the domain of geology. If Geology therefore is to continue worthy of its name as the science of the earth, it must take cognisance of these recent contributions from other sciences. It can no longer be content to begin its annals with the records of the oldest rocks, but must endeavour to grope its way through the ages which preceded the formation of any rocks. Thanks to the results achieved with the telescope, the spectroscope, and the chemical laboratory, the story of these earliest ages of our earth is every year becoming more definite and intelligible.

I. Relations of the Earth in the Solar System.

As a prelude to the study of the structure and history of the earth, some of the general relations of our planet to the solar system may here be noticed. The investigations of recent years showing the community of substance between the different members of that system, have revived and given a new form and meaning to the well-known nebular hypothesis of Kant, Laplace and W. Herschel, which sketched the progress of the system from the state of an original nebula to its existing condition of a central incandescent sun with surrounding cool planetary bodies. According to this hypothesis, the nebula, originally diffused at least as far as the furthest member of the system, began to condense towards the centre, and in so doing threw off or left behind successive rings which on disruption and further condensation assumed the form of planets, sometimes with a further formation of rings, which in the case of Saturn remain, though in other planets they have broken up and united into satellites.

Accepting this view, we should expect the matter composing the various members of the solar system to be everywhere nearly the same. The fact of condensation round centres, however, indicates at least differences of density throughout the nebula. That the materials composing the nebula may have arranged themselves according to their respective densities, the lightest occupying the exterior and the heaviest the interior of the mass, is suggested by a comparison of the densities of the various planets. These densities

are usually estimated as in the following table, that of the earth being taken as the unit:—

Density of the Sun		0·25
„	Mercury	1·12
„	Venus	1·03
„	Earth	1·00
„	Mars	0·70
„	Jupiter	0·24
„	Saturn	0·13
„	Uranus	0·17
„	Neptune	0·16

It is to be observed, however, that "the densities here given are mean densities, assuming that the *apparent* size of the planet or sun is the *true* size, *i.e.*, making no allowance for thousands of miles deep of cloudy atmosphere. Hence the numbers for Jupiter, Saturn, and Uranus are certainly too small, that for the sun, much too small."[1] Taking the figures as they stand, while they do not indicate a strict progression in the diminution of density, they state that the planets near the sun possess a density about twice as great as that of granite, but that those lying towards the outer limits of the system are composed of matter as light as cork. Again, in some cases, a similar relation has been observed between the densities of the satellites and their primaries. The moon, for example, has a density little more than half that of the earth. The first satellite of Jupiter is less dense, though the other three are found to be more dense than the planet. Further, in the condition of the earth itself, a very light gaseous atmosphere forms the outer portion, beneath which lies a heavier layer of water, while within these two envelopes the materials forming the solid substance of the planet are so arranged that the outer layer or crust has only about half the density of the whole globe. Mr. Lockyer finds in the sun also evidence of the same tendency towards a stratified arrangement in accordance with relative densities, as will be immediately further alluded to.

There seems therefore to be much probability in the hypothesis that, in the gradual condensation of the original nebula, each successive mass left behind represented the density of its parent shell, and consisted of progressively heavier matter. The remoter planets, with their low density and vast absorbing atmospheres, may be supposed to consist of metalloids like the outer parts of the sun's atmosphere, while the interior planets are no doubt mainly metallic. The rupture of each planetary ring would, it is conceived, raise the temperature of the resultant nebulous planet to such a height as to allow the vapours to rearrange themselves by degrees in successive layers, or rather shells, according to density. And when the planet gave off a satellite, that body might be expected to possess the composition and density of the outer layers of its primary.[2]

[1] Professor Tait, MS. note.

[2] Lockyer in Prestwich's *Inaugural Lecture*, Oxford, 1875, and in Manchester Lectures, *Why the Earth's Chemistry is as it is.* Readers interested in the historical development of geological opinion will find much suggestive matter bearing on the questions discussed above, in De la Beche's "Researches in Theoretical Geology," 1834,—a work notably in advance of its time.

For many years the only evidence available as to the actual composition of other heavenly bodies than our own earth was furnished by the *aerolites*, *meteorites*, or falling stars, which from time to time have entered our atmosphere from planetary space, and have descended upon the surface of the globe. Subjected to chemical analysis these foreign bodies show considerable diversities of composition; but in no case have they yet revealed the existence of any element not already recognised among terrestrial materials. Upwards of twenty of our elements have been detected in aerolites, sometimes in the free state, sometimes combined with each other. More than half of them are metals, including iron, nickel, manganese, calcium, sodium, and potassium. There occur also carbon, silicon, phosphorus, sulphur, oxygen, nitrogen, and hydrogen. In some of their combinations these elements, as found in the meteoric stones, differ from their mode of occurrence in the accessible parts of the earth. Iron, for example, occurs as native metal, alloyed with a variable proportion (6 to 10 per cent.) of metallic nickel. But in other respects they closely resemble some of the familiar materials of the earth's rocky crust. Thus we have such minerals as chromic iron, pyrite, apatite, olivine, augite, enstatite, hornblende, and labradorite. No more convincing proof could be desired that some at least of the other members of the solar system are formed of the same materials as compose the earth.[1]

But in recent years a far more precise and generally available method of research into the composition of the heavenly bodies has been found in the application of the spectroscope. By means of this instrument, the light emitted from self-luminous bodies can be analysed in such a way as to show what elements are present in their intensely hot luminous vapour. When the light of the incandescent vapour of a metal is allowed to pass through a properly-arranged prism, it is seen to give a spectrum consisting of transverse bright lines only. This is termed a *radiation-spectrum*. Each element appears to have its own characteristic arrangement of lines, which in general retain the same relative position, intensity, and colours. Moreover, gases and the vapours of solid bodies are found to intercept those rays of light which they themselves emit. The spectrum of sodium-vapour, for example, shows two bright orange lines. If therefore white light from some hotter light-source passes through the vapour of sodium, these two bright lines become dark lines, the light being exactly cut off which would have been given out by the sodium itself. This is called an *absorption-spectrum*.

From this method of examination it has been inferred that many

[1] Partsch, *Die Meteoriten*, Vienna, 1843; Rose, *Abhand. königl. Akad.* Berlin, 1863. Rammelsberg, *Die Chemische Natur der Meteoriten*, 1870. The student will find a valuable monograph on the structure and origin of meteorites in the second part of Daubrée's *Études Synthétiques de Géologie Expérimentale*, 1879. See also *A Chapter on the History of Meteorites*, by Dr. W. Flight, *Geol. Mag.* 1875, and a very interesting account of a recent meteoric shower, and of the microscopic constitution of the fragments by J. Galle and A. von Lasaulx in *Monatsbericht königl. Akad.* Berlin, July, 1879.

of the elements of which our earth is composed must exist in the state of incandescent vapour in the atmosphere of the sun. Thirty-two metals have been thus identified, including aluminium, barium, manganese, lead, calcium, cobalt, potassium, iron, zinc, copper, nickel, sodium and magnesium. These elements, or at least substances which give the same groups of lines as the terrestrial elements with which they have been identified, do not occur promiscuously diffused throughout the outer mass of the sun. According to Mr. Lockyer's observations they appear to succeed each other in relation to their respective densities. Thus the coronal atmosphere which, as seen in total eclipses, extends to so prodigious a distance beyond the disc of the sun, consists mainly of subincandescent hydrogen and another element which may be new. Beneath this external vaporous envelope lies the chromosphere where the vapours of incandescent hydrogen, calcium, and magnesium can be detected. Further inward the spot-zone shows the presence of sodium, titanium, &c.; while still lower, a layer (the *reversing* layer) of intensely hot vapours, lying probably next to the inner brilliant photosphere gives spectroscopic evidence of the existence of incandescent iron, manganese, cobalt, nickel, copper, and other well-known terrestrial metals.[1]

It is to be observed, however, that in these spectroscopic researches the decomposition of the elements by electrical action was not considered. The conclusions embodied in the foregoing paragraph have been founded on the idea that the lines seen in the spectrum of any element are all due to the vibrations of the molecules of that element. But Mr. Lockyer has quite recently suggested that this view may after all be but a rough approximation to the truth, and that it may be more accurate to say, as a result of the facts already acquired, that there exist basic elements common to calcium, iron, &c., and to the solar atmosphere.

The spectroscope has likewise been successfully applied by Mr. Huggins and others to the observation of the fixed stars and nebulæ, with the result of establishing a similarity of elements between our own system and other bodies in sidereal space. In the radiation spectra of nebulæ Mr. Huggins finds the hydrogen lines very prominent; and he conceives that they may be glowing masses of that element. Professor Tait has suggested, on the other hand, that they are more probably clouds of stones frequently colliding and thus giving off incandescent gases. Sir William Thomson appears to favour this view. Among the fixed stars absorption spectra have been recognised, pointing to a structure resembling that of our sun, viz., an incandescent nucleus which may be solid or liquid or of very highly compressed gas, but which gives a continuous spectrum,

[1] On spectroscopic research as applied to the sun, see Kirchhoff and Bunsen, *Researches on Solar Spectrum*, &c., Macmillan, 1863; Angstrom, *Recherches sur le Spectre normal du Soleil*; Lockyer, *Solar Physics*, 1873, and *Studies in Spectrum Analysis* (International Series), 1878; Huggins and Miller, *Proc. Roy. Soc.* xii. *Phil. Trans.* 1864; Roscoe's *Spectrum Analysis*, with authorities there cited.

and which is surrounded with an atmosphere of glowing vapour.[1] According to Mr. Lockyer, those stars which have the highest temperature have the simplest spectra, and in proportion as they cool their materials become more and more differentiated into what we call elements. He remarks that the most brilliant or hottest stars show in their spectra only the lines of gases, as hydrogen. Cooler stars, like our sun, give indications of the presence, in addition, of the metals—magnesium, sodium, calcium, iron. A still lower temperature he regards as marked by the appearance of the other metals, metalloids, and compounds.[2] The sun would thus be a star considerably advanced in the process of differentiation or association of its atoms. It contains, so far as we know, no metalloid except carbon, and possibly oxygen, nor any compound, while stars like Sirius show the presence only of hydrogen, with but a feeble proportion of metallic vapours; and on the other hand, the red stars indicate by their spectra that their metallic vapours have entered into combination, whence it is inferred that their temperature is lower than that of our sun.

II. FORM AND SIZE OF THE EARTH.

Further confirmation of the foregoing views as to the order of planetary evolution is furnished by the form of the earth and the arrangement of its component materials.

That the earth is an oblate spheroid, and not a perfectly spherical globe, was discovered and demonstrated by Newton. He even calculated the amount of ellipticity long before any measurement had confirmed such a conclusion. During the present century numerous arcs of the meridian have been measured, chiefly in the northern hemisphere. From a series made by different observers between the latitudes of Sweden and the Cape of Good Hope, Bessel obtained the following data for the dimensions of the earth:—

Equatorial diameter . .	41,847,192 feet, or	7925·604 miles.
Polar diameter	41,707,314 „	7899·114 „
Amount of polar flattening	139,768 „	26·471 „

The equatorial circumference is thus a little less than 25,000 miles, and the difference between the polar and equatorial diameters (nearly 26½ miles) amounts to about $\frac{1}{300}$th of the equatorial diameter.[3] More recently, however, it has been shown that the oblate spheroid indicated by these measurements is not a symmetrical body, the equatorial circumference being an ellipse instead of a circle. The greater axis of the equator lies in long. 8° 15′ W.—a meridian passing through Ireland, Portugal and the north-west corner of Africa, and cutting off the north-east corner of Asia in the opposite hemisphere.[4]

[1] Huggins, *Proc. Roy. Soc.* 1863–66, and *Brit. Assoc. Lecture* (Nottingham, 1866); Huggins and Miller, *Phil. Trans.* 1864.

[2] Lockyer, *Comptes-rendus*, Dec. 1873.

[3] Herschel, *Astronomy*, p. 139.

[4] A. R. Clarke, *Phil. Mag.* August 1878; *Encyclopædia Britannica*, 9th edit. x. 172.

The polar flattening, established by measurement and calculation as that which would necessarily have been assumed by an originally plastic globe in obedience to the movement of rotation, has been cited as evidence that the earth was once in a plastic condition. Taken in connection with the analogies supplied by the sun and other heavenly bodies, this inference seems well grounded.[1]

Though the general spheroidal form of our planet, and possibly the general distribution of sea and land, are referable to the early effects of rotation on a fluid or viscous mass, it is certain that the present details of its surface-contours are of comparatively recent date. Speculations have been made as to what may have been the earliest character of the solid surface, whether it was smooth or rough, and particularly whether it was marked by any indication of the existing continental elevations and oceanic depressions. So far as we can reason from geological evidence, there is no proof of any uniform superficies having ever existed. Most probably the first formed crust broke up irregularly, and not until after many successive corrugations did the surface acquire stability. Some writers have imagined that at first the ocean spread over the whole surface of the planet. But of this there is not only no evidence, but good reason for believing that it could never have taken place. As will be alluded to in a later page, the preponderance of water in the southern hemisphere seems to indicate some excess of density in that hemisphere. This excess can hardly have been produced by any change since the materials of the interior ceased to be mobile; it must therefore be at least as ancient as the condensation of water on the earth's surface. Hence there was probably from the beginning a tendency in the ocean to accumulate in the southern rather than in the northern hemisphere.

That land existed from the earliest ages of which we have any record in rock-formations, is evident from the obvious fact that these formations themselves consist in great measure of materials derived from the waste of land. When the student in a later part of this volume is presented with the proofs of the existence of enormous masses of sedimentary deposits even among some of the oldest geological systems, he will perceive how important must have been the tracts of land that could furnish such piles of detritus.

The tendency of modern research is to give probability to

[1] It has been recently opposed, however, by Mohr (*Geschichte der Erde*, p. 472), who, adopting a suggestion long ago made by Playfair, has endeavoured to show that the polar flattening can be accounted for by greater denudation of the polar tracts, exposed as these have been by the heaping up of the oceanic waters towards the equator in consequence of rotation. He dwells chiefly on the effects of glaciers in lowering the land, but as Pfaff has pointed out, the work of erosion is chiefly performed by other atmospheric forces that operate rather towards the equator than the poles (*Allgemeine Geologie als exacte Wissenschaft*, p. 6). Compare Naumann, *Neues Jahrb.* 1871, p. 250. Nevertheless, Mohr has undoubtedly recalled attention to a conceivable cause by which, in spite of polar elevation or equatorial subsidence, the external form of the planet might be preserved.

the conception, first outlined by Kant, that not only in our own solar system, but throughout the regions of space, there has been a common plan of evolution, and that the matter diffused through space in nebulæ, stars, and planets is substantially the same as that with which we are familiar. Hence the study of the structure and probable history of the sun and the other heavenly bodies comes to possess an evident geological interest, seeing that it may yet enable us to carry back the story of our planet far beyond the domain of ordinary geological evidence, and upon data not less trustworthy than those furnished by the rocks of the earth's crust.

III. THE MOVEMENTS OF THE EARTH IN THEIR GEOLOGICAL RELATIONS.

We are here concerned only with those aspects of the earth's motions which materially influence the progress of geological phenomena.

§ 1. **Rotation.**—In consequence of its angular momentum at its original separation, the earth rotates on its axis. The rate of rotation has once been much more rapid than it now is (p. 20). At present a complete rotation is performed in about twenty-four hours, and to it is due the succession of day and night. So far as observation has yet gone, this movement is uniform, though recent calculations of the influence of the tides in retarding rotation tend to show that a very slow diminution of the angular velocity is in progress. If this be so, the length of the day and night will slowly increase until finally the duration of the day and that of the year will be equal. The earth will then have reached the condition into which the moon has passed relatively to the earth, one half being in continual day, the other in perpetual night.

The linear velocity due to rotation varies in different places, according to their position on the surface of the planet. At each pole there can be no velocity, but from these two points towards the equator there is a continually increasing rapidity of motion, till at the equator it is equal to a rate of 507 yards in a second.

To the rotation of the earth are due certain remarkable influences upon currents of air circulating either towards the equator or towards the poles. Currents which move from polar latitudes travel from parts of the earth's surface where the velocity due to rotation is small to others where it is great. Hence they lag behind, and their course is bent more and more westward. An air current quitting the north polar or north temperate regions as a north wind is deflected out of its course and becomes a north-east wind. On the opposite side of the equator a similar current setting out straight for the equator is changed into a south-east wind. This is the reason why the well-known Trade-winds have their characteristic westward deflection. On the other hand, a current setting out northwards or southwards

from the equator passes into regions having a less velocity due to rotation than it possesses itself, and hence it travels on in advance and appears to be gradually deflected eastward. The aerial currents blowing steadily across the surface of the ocean produce oceanic currents which have a westward tendency indirectly communicated to them from the effects of rotation.

It has been maintained by Von Baer,[1] and the statement has been accepted as a general law by some writers, that a certain deflection is experienced by rivers that flow in a meridional direction, like the Volga. Those travelling polewards are asserted to press upon their eastern rather than their western banks, while those which run in the opposite direction are stated to be thrown more against the western than the eastern. When, however, we consider the comparatively small volume, slow motion, and continually meandering course of rivers, it may reasonably be doubted whether any effects of this *vera causa* have yet been observed.[2]

§ 2. **Revolution.**—Besides turning on its axis, the globe performs a movement round the sun, termed revolution. This movement, accomplished in rather more than 365 days, determines for us the length of our year, which is, in fact, merely the time required for one complete revolution. The path or orbit followed by the earth round the sun is not a perfect circle but an ellipse, with the sun in one of the foci, the mean distance of the earth from the sun being 92,400,000 miles. By slow secular variations the form of the orbit alternately approaches to and recedes from that of a circle. At the nearest possible approach between the two bodies, owing to change in the ellipticity of the orbit, the earth is 14,368,200 miles nearer the sun than when at its greatest possible distance. These maxima and minima of distance occur at vast intervals of time. The last considerable eccentricity took place about 200,000 years ago, and the previous one more than half a million years earlier. Since the amount of heat received by the earth from the sun is inversely as the square of the distance, eccentricity may have had in past time much effect upon the climate of the earth, as will be pointed out further on (§ 8).

§ 3. **Precession of the Equinoxes.**—If the axis of the earth were perpendicular to the plane of its orbit, there would be equal day and night all the year round. But it is really inclined to that plane at an angle of $23\frac{1}{2}°$. Hence our hemisphere is alternately presented to and turned away from the sun, and in this way brings the familiar alternation of the seasons. Again, were the earth a perfect sphere of uniform density throughout, the position of its axis of rotation would not be changed by attractions of external bodies. But owing to the

[1] "Ueber ein allgemeines Gesetz in der Gestaltung der Flussbetten." *Bull. Acad. St. Petersburg*, ii. (1860). See also Ferrel on the motions of fluids and solids relatively to the earth's surface. *Camb. (Mass.) Math. Monthly*, vols. i. and ii. (1859–60). Dulk. *Z. Deutsch. Geol. Ges.* xxxi. (1879) p. 224.

[2] See E. Dunker, *Zeitsch. für die gesammten Naturwissenschaften*, 1875, p. 463.

protuberance along the equatorial regions, the attraction chiefly of the moon and sun tends to pull the axis aside, or to make it describe a conical movement like that of the axis of a top round the vertical. Hence each pole points successively to different stars. This movement, called the precession of the equinoxes, in combination with another smaller movement, due to the attraction of the moon (called *nutation*), completes its cycle in 21,000 years. At present the winter in the northern hemisphere coincides with the earth's nearest approach to the sun, or *perihelion*. In 10,500 years hence it will take place when the earth is at the farthest part of its orbit from the sun, or in *aphelion*. This movement acquires great importance when considered in connexion with the secular variations in the eccentricity of the orbit (§ 8).

§ 4. **Change in the Obliquity of the Ecliptic.**—The angle at which the axis of the earth is inclined to the plane of its orbit does not remain strictly constant. It oscillates through long periods of time to the extent of about a degree and a half, or perhaps a little more, on either side of the mean. According to Dr. Croll,[1] this oscillation must have considerably affected former conditions of climate on the earth, since, when the obliquity is at its maximum, the polar regions receive about eight and a half days more of heat than they do at present—that is, about as much heat as lat. 76° enjoys at this day. This movement must have augmented the geological effects of precession, to which reference has just been made, and which are described in § 8.

§ 5. **Stability of the Earth's Axis.**—That the axis of the earth's rotation has successively shifted, and consequently that the poles have wandered to different points on the surface of the globe, has been maintained by geologists as the only possible explanation of certain remarkable conditions of climate, which can be proved to have formerly obtained within the Arctic Circle. Even as far north as lat. 81° 45′ abundant remains of a vegetation indicative of a warm climate, and including a bed of coal 25 to 30 feet thick, have been found *in situ*.[2] It is contended that where these plants lived the ground could not have been permanently frozen or covered for most of the year with thick snow. In explanation of the difficulty, it has been suggested that the north pole did not occupy its present position, and that the locality where the plants occur lay in more southerly latitudes. Without at present entering on the discussion of the question whether the geological evidence necessarily requires so important a geographical change, let us consider how far a shifting of the axis of rotation has been a possible cause of change during that section of geological time for which there are records among the stratified rocks.

From the time of Laplace[3] astronomers have strenuously denied

[1] Croll, *Trans. Geol. Soc. Glasgow*, ii. 177.
[2] Fielden and Heer, *Quart. Journ. Geol. Soc.* Nov. 1877.
[3] *Mécanique céleste*, tome v. p. 14.

the possibility of any sensible change in the position of the axis of rotation. It has been urged that, since the planet acquired its present oblate spheroidal form, nothing but an utterly incredible amount of deformation could overcome the greater centrifugal force of the equatorial protuberance. It is certain, however, that the axis of rotation does not strictly coincide with the principal axis of inertia. Though the angular difference between them must always have been small, we can, without having recourse to any extra-mundane influence, recognise two causes which, whether or not they may suffice to produce any change in the position of the main axis of inertia, undoubtedly tend to do so. In the first place a widespread upheaval or depression of certain unsymmetrically arranged portions of the surface to a considerable amount would tend to shift that axis. In the second place an analogous result might arise from the denudation of continental masses of land and the consequent filling up of sea-basins. Sir William Thomson freely concedes the physical possibility of such changes. "We may not merely admit," he says, "but assert as highly probable, that the axis of maximum inertia and axis of rotation, always very near one another, may have been in ancient times very far from their present geographical position, and may have gradually shifted through 10, 20, 30, 40, or more degrees, without at any time any perceptible sudden disturbance of either land or water."[1] But though, in the earlier ages of the planet's history, stupendous deformations may have occurred, and the axis of rotation may have often shifted, it is only the alterations which can possibly have occurred during the accumulation of the stratified rocks that need to be taken into account in connexion with former changes of climate. If it can be shown therefore that the geographical revolutions necessary to shift the axis are incredibly stupendous in amount, improbable in their distribution, and not really demanded by geological evidence, we may reasonably withhold our belief from this alleged cause of the changes of climate during geological history.

It has been estimated by Sir William Thomson "that an elevation of 600 feet, over a tract of the earth's surface 1000 miles square and 10 miles in thickness, would only alter the position of the principal axis by one-third of a second, or 34 feet."[2] Mr. George Darwin has shown that on the supposition of the earth's complete rigidity no redistribution of matter in new continents could ever shift the pole from its primitive position more than 3°, but that, if its degree of rigidity is consistent with a periodical re-adjustment to a new form of equilibrium, the pole may have wandered some 10° or 15° from its primitive position, or have made a smaller excursion and returned to near its old place. In order, however, that these maximum effects should be produced, it would be necessary that

[1] *Brit. Assoc. Rep.* (1876), Sections, p. 11.

[2] *Trans. Geol. Soc. Glasgow*, iv. p. 313. The situation of the supposed area of upheaval on the earth's surface is not stated.

each elevated area should have an area of depression corresponding in size and diametrically opposite to it, that they should lie on the same complete meridian, and that they should both be situated in lat. 45°. With all these coincident favourable circumstances, an effective elevation of $\frac{1}{100}$ of the earth's surface to the extent of 10,000 feet would shift the pole $11\frac{1}{3}'$; a similar elevation of $\frac{1}{20}$ would move it $1° 46\frac{1}{4}'$; of $\frac{1}{10}$, $3° 17'$; and of $\frac{1}{5}$, $8° 4\frac{1}{4}'$. Mr. Darwin admits these to be superior limits to what is possible, and that, on the supposition of intumescence or contraction under the regions in question, the deflection of the pole might be reduced to a quite insignificant amount.[1]

Under the most favourable conditions, therefore, the possible amount of deviation of the pole from its first position would appear to have been too small to have seriously influenced the climates of the globe within geological history. If we grant that these changes were cumulative, and that the superior limit of deflection was reached only after a long series of concurrent elevations and depressions, we must suppose that no movements took place elsewhere to counteract the effect of those about lat. 45° in the two hemispheres. But this is hardly credible. A glance at a geographical globe suffices to show how large a mass of land exists now both to the north and south of that latitude, especially in the northern hemisphere, and that the deepest parts of the ocean are not antipodal to the greatest heights of the land. These features of the earth's surface are of old standing. There seems, indeed, to be no geological evidence in favour of any such geographical changes as could have produced even the comparatively small displacement of the axis considered possible by Mr. G. Darwin.

In an ingenious suggestion, Dr. John Evans contended that, even without any sensible change in the position of the axis of rotation of the nucleus of the globe, there might be very considerable changes of latitude due to disturbance of the equilibrium of the shell by the upheaval or removal of masses of land between the equator and the poles, and to the consequent sliding of the shell over the nucleus until the equilibrium was restored.[2] In a recent address he has precisely formulated his hypothesis as a question to be determined mathematically.[3] The solution of the problem has been worked out by the Rev. J. F. Twisden, who arrives at the conclusion that even the large amount of geographical change postulated by Dr. Evans could only displace the earth's axis of figure to the extent of less than 10′ of angle, that a displacement of as much as 10° or 15° could be effected only if the heights and depths of the areas elevated and depressed exceeded by many times the heights of the highest mountains, that under no circumstances could a displacement of 20° be effected by a transfer of matter of less amount than about a sixth part of the whole equatorial bulge, and that even

[1] *Phil. Trans.* Nov. 1876. [2] *Proc. Roy. Soc.* xv. p. 46 (1867).
[3] *Q. J. Geol. Soc.* (1876) p. 62.

this extreme amount would not necessarily alter the position of the axis of figure.[1]

Against any hypothesis which assumes a thin crust enclosing a liquid or viscous interior—weighty and indeed insuperable objections have been urged. It has been suggested, however, that the almost universal traces of present or former volcanic action, the evidence from the compressed strata in mountain regions that the crust of the earth must have a capacity for slipping towards certain lines, the great amount of horizontal compression of strata which can be proved to have been accomplished, and the secular changes of climate—notably the former warm climate near the north pole—furnish grounds for inquiry whether the doctrine of a fluid substratum over a rigid nucleus, which has been urged by several able writers, would not be compatible with mechanical considerations, and whether, under those circumstances, changes in latitude would not result from unequal thickening of the crust.[2] This question of the internal condition of the globe is discussed at p. 49.

§ 6. **Changes of the Earth's Centre of Gravity.**—If the centre of gravity in our planet, as pointed out by Herschel, be not coincident with the centre of figure, but lies somewhat to the south of it, any variation in its position will affect the ocean, which of course adjusts itself in relation to the earth's centre of gravity. How far any redistribution of the matter within the earth in such a way as to affect the present equilibrium is now possible, we cannot tell. But certain revolutions at the surface may from time to time produce changes of this kind. The accumulation of ice which, as will be immediately described (§ 8), is supposed to gather round one pole during the maximum of eccentricity, will displace the centre of gravity, and, as the result of this change, will raise the level of the ocean in the glacial hemisphere.[3] Dr. Croll has estimated that, if the present mass of ice in the southern hemisphere is taken at 1000 feet thick extending down to lat. 60°, the transference of this mass to the northern hemisphere would raise the level of the sea 80 feet at the north pole. Other methods of calculation give different results. Mr. Heath puts the rise at 128 feet; Archdeacon Pratt makes it more; while the Rev. O. Fisher gives it at 409 feet.[4] More recently, in returning to this question, Dr. Croll remarks "that the removal of two miles of ice from the Antarctic continent [and at present the mass of ice there is probably thicker than that] would displace the centre of gravity 190 feet, and the formation of a mass of ice equal to the one-half of this, on the Arctic regions, would carry the centre of gravity 95 feet farther, giving in all a

[1] *Q. J. Geol. Soc.* (1878) xxxiv. p. 41. See also E. Hill, *Geol. Mag.* v. (2nd ser.) pp. 262, 479. O. Fisher, *op. cit.* pp. 291, 551.

[2] O. Fisher, *Geol. Mag.*, 1878, p. 552.

[3] Adhemar, *Révolutions de la Mer*, 1840.

[4] Croll, in *Reader* for 2nd September, 1865, and *Phil. Mag.*, April, 1866; Heath, *Phil. Mag.*, April, 1869; Pratt, *Phil. Mag.*, March, 1866; Fisher, *Reader*, 10th February, 1866.

total displacement of 285 feet, thus producing a rise of level at the north pole of 285 feet, and in the latitude of Edinburgh of 234 feet." A very considerable additional displacement would arise from the increment of water to the mass of the ocean by the melting of the ice. Supposing half of the two miles of Antarctic ice to be replaced by an ice-cap of similar extent and one mile thick in the northern hemisphere, the other half being melted into water and increasing the mass of the ocean, Dr. Croll estimates that from this source an extra 200 feet of rise would take place in the general ocean level, so that there would be a rise of 485 feet at the north pole, and 434 feet in the latitude of Edinburgh.[1] An intermittent submergence and emergence of the low polar lands might thus be due to the alternate shifting of the centre of gravity.

To what extent this cause has actually come into operation in past time cannot at present be determined. It has been suggested that the "raised beaches" or old sea-terraces, so numerous at various heights in the north-west of Europe, might be due to the transference of the oceanic waters and not to any subterranean movement, as generally believed. But if such had been their origin, they ought to have shown evidence of a gradual and uniform decline in elevation from north to south. No such feature, however, has been detected. On the contrary, the levels of the terraces vary within comparatively short distances. Though numerous on both sides of Scotland, they disappear among the Orkney and Shetland islands, although these localities were admirably adapted for their formation and preservation.[2] The conclusion must be drawn that the "raised beaches" cannot be adduced as evidence of changes of the earth's centre of gravity, but are due to local and irregular subterranean movement. (See Book III. Part I. Section iii. § 1.)

§ 7. **Results of the Attractive Influence of Sun and Moon on the Geological Condition of the Earth.**—Many speculations have been offered to account for supposed former greater intensity of geological activity on the surface of the globe. Two causes for such greater intensity may be adduced. In the first place, if the earth has cooled down from an original molten condition, it has lost, in cooling, a vast amount of potential geological energy. It does not necessarily follow, however, that the geological phenomena resulting from internal temperature have, during the time recorded in the accessible part of the earth's crust, been steadily decreasing in magnitude. We might, on the contrary, contend that the increased resistance of a thickening cooled crust may rather have hitherto intensified the manifestations of subterranean activity by augmenting the resistance to be overcome. In the second place, the earth may have been more powerfully affected by external causes, such as the greater heat of the sun, and the greater proximity of the moon.

[1] Croll, *Geol. Mag.*, new series, i. (1874), p. 347; *Climate and Time*, chaps. xxiii. and xxiv.

[2] *Nature*, xvi. (1877) p. 415.

That the formerly larger amount of solar heat received by the surface of our planet must have produced warmer climates and more rapid evaporation with greater rainfall and the important chain of geological changes which such an increase would introduce, appears in every way probable, though the geologist has not yet been able to observe any indisputable indication of such a former intensity of superficial changes.

Mr. George H. Darwin, in recently investigating the bodily tides of viscous spheroids, has brought forward some remarkable results bearing on the question of the possibility that geological operations, both internal and superficial, may have been once greatly more gigantic and rapid than they are now.[1] He assumes the earth to be a homogeneous spheroid and to have possessed a certain small viscosity,[2] and he calculates the internal tidal friction in such a mass exposed to the attraction of moon and sun, and the consequences which these bodily tides have produced. He finds that the length of our day and month have greatly increased, that the moon's distance has likewise augmented, that the obliquity of the ecliptic has diminished, that a large amount of hypogene heat has been generated by the internal tidal friction, and that these changes may all have transpired within comparatively so short a period (57,000,000 years) as to place them quite probably within the limits of ordinary geological history. According to his estimate, 46,300,000 years ago the length of the sidereal day was fifteen and a half hours, the moon's distance in mean radii of the earth was 46·8 as compared with 60·4 at the present time. But 56,810,000 years back the length of the day was only $6\frac{3}{4}$ hours, or less than a quarter of its present value, the moon's distance was only nine earth's radii, while the lunar month lasted not more than about a day and a half (1·58), or $\frac{1}{17}$ of its present duration. He arrives at the deduction that the energy lost by internal tidal friction in the earth's mass is converted into heat at such a rate that the amount lost during 57,000,000 years, if it were all applied at once, and if the earth had the specific heat of iron, would raise the temperature of the whole planet's mass 1,700° Fahrenheit, but that the distribution of this heat generation has been such as not to interfere with the normal augmentation of temperature downward due to secular cooling, and the conclusion drawn therefrom by Sir William Thomson. Mr. Darwin further concludes from his hypothesis that the ellipticity of the earth's figure having been continually diminishing, "the polar regions must have been ever rising and the equatorial ones falling, though as the ocean followed these changes they might quite well have left no geological traces. The tides must have been very

[1] *Phil. Trans.*, 1879, Parts i. and ii.

[2] The degree of viscosity assumed is such that "thirteen and a half tons to the square inch acting for twenty-four hours on a slab an inch thick displaces the upper surface relatively to the lower through one-tenth of an inch. It is obvious," says Mr. Darwin, "that such a substance as this would be called a solid in ordinary parlance, and in the tidal problem this must be regarded as a very small viscosity." *Op. cit.* p. 531.

much more frequent and larger, and accordingly the rate of oceanic denudation much accelerated. The more rapid alternation of day and night[1] would probably lead to more sudden and violent storms, and the increased rotation of the earth would augment the violence of the trade-winds, which in their turn would affect oceanic currents."[2] As above stated, no facts yet revealed by the geological record compel the admission of more violent superficial action in former times than now. But though the facts do not of themselves lead to such an admission, it is proper to inquire whether any of them are hostile to it. It will be shown in Book VI. that even as far back as early Palæozoic times, that is, as far into the past as the history of organised life can be traced, sedimentation took place very much as it does now. Sheets of fine mud and silt were pitted with rain-drops, ribbed with ripple-marks, and furrowed by crawling worms exactly as they now are on the shores of any modern estuary. These surfaces were quietly buried under succeeding sediment of a similar kind, and this for hundreds and thousands of feet. Nothing indicates violence; all the evidence favours tranquil deposit. If, therefore, Mr. Darwin's hypothesis be accepted, we must conclude either that it does not necessarily involve such violent superficial operations as he supposes, or that even the oldest sedimentary formations do not date back to a time when the influence of increased rotation could make itself evident in sedimentation, that is to say, on Mr. Darwin's hypothesis, the most ancient fossiliferous rocks cannot be nearly as much as 57,000,000 years old.

§ 8. **Climate in its Geological Relations.**—In subsequent parts of this volume the data will be given from which we learn that the climates of the earth have formerly been considerably different from those which at present prevail. A consideration of the history of the solar system would of itself suggest the inference that on the whole the climates of early geological periods must have been warmer. The sun's heat was greater, probably the amount of it received by the earth was likewise greater, while there would be for some time a sensible influence of the planet's own internal heat upon the general temperature of the whole globe.[3] Although arguments based upon the probable climatal necessities of extinct species and genera of plants and animals must be used with extreme caution, it may be asserted with some confidence that from the vast areas over which many Palæozoic molluscs have been traced alike in the eastern and the western hemispheres, the climates of the globe in Palæozoic time were probably much more uniform than they now

[1] According to his calculation, the year 57,000,000 of years ago contained 1300 days instead of 365.

[2] *Op. cit.* p. 532.

[3] As Professor Tait has suggested, we can conceive that the former greater heat of the sun may have raised such vast clouds of absorbing vapour round that luminary as to prevent the effective amount of radiation of heat to the earth's surface from being greater than at present; while on the other hand, a similar supposition may be made with reference to the greater amount of vapour which increased solar radiation would raise to be condensed in the earth's atmosphere. *Recent Advances in Physical Science*, 1876, p. 174.

are. There appears to have been a gradual lowering of the general temperature during past geological time, accompanied by a tendency towards greater extremes of climate. But there are proofs also that at longer or shorter intervals cold cycles have intervened. The glacial period, for example, preceded our own time, and in successive geological formations indications of more or less value have been found that point to a prevalence of ice in what are now temperate regions.

Various theories have been proposed in explanation of such alternations of climate. Some of these have appealed to a change in the position of the earth's axis relatively to the mass of the planet (*ante*, § 5). Others have been based on the notion that the earth may have passed through hot and cold regions of space. Others, again, have called in the effects of terrestrial changes, such as the distribution of land and sea, on the assumption that elevation of land about the poles must cool the temperature of the globe, while elevation round the equator would raise it.[1] But the changes of temperature have affected vast areas of the earth's surface, while there is not only no proof of any such enormous vicissitudes in physical geography as would be required, but good grounds for believing that the present terrestrial and oceanic areas have remained on the whole on the same sites from very early geological time. Moreover, as evidence has accumulated in favour of periodic alternations of climate, the conviction has been strengthened that no mere local changes could have sufficed, but that secular variations in climate must be assigned to some general and probably recurring cause.

By degrees geologists accustomed themselves to the belief that the cold of the Glacial Period was not due to mere terrestrial changes, but was to be explained somehow as the result of cosmical causes. Of various suggestions as to the probable nature and operation of these causes, one deserves careful consideration—change in the eccentricity of the earth's orbit. Sir John Herschel [2] pointed out many years ago that the direct effect of a high condition of eccentricity is to produce an unusually cold winter followed by a correspondingly hot summer on the hemisphere whose winter occurs in aphelion, while an equable condition of climate will at the same time prevail on the opposite hemisphere. But both hemispheres must receive precisely the same amount of solar heat, because the deficiency of heat resulting from the sun's greater distance during one part of the year is exactly compensated by the greater length of that season. Sir John Herschel even considered that the direct effects of eccentricity must thus be nearly neutralised.[3] As a like verdict was afterwards given by Arago, Humboldt, and others,

[1] In Lyell's *Principles of Geology*, this doctrine of the influence of geographical changes is maintained.

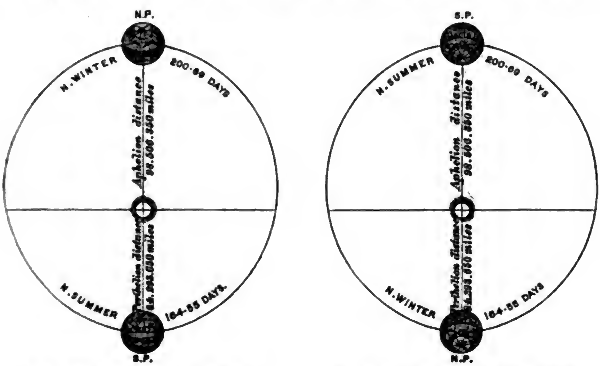
[2] *Trans. Geol. Soc.*, vol. iii. p. 293 (2nd series).

[3] *Cabinet Cyclopædia*, sec. 315; *Outlines of Astronomy*, sec. 368.

geologists were satisfied that no important change of climate could be attributed to change of eccentricity.

It is to the luminous memoirs of Dr. James Croll that geology is indebted for the first fruitful suggestion in this matter, and for the subsequent elaborate development of the whole subject of the physical causes on which climate depends. His researches will be found in detail in his volume, *Climate and Time*, 1875. He has been good enough, however, to draw up the following abstract of them for the present work.

"Assuming the mean distance of the sun to be 92,400,000 miles, then when the eccentricity is at its superior limit, ·07775, the distance of the sun from the earth, when the latter is in the aphelion of its orbit, is no less than 99,584,100 miles, and when in the perihelion it is only 85,215,900 miles. The earth is, therefore, 14,368,200 miles farther from the sun in the former than in the latter position. The direct heat of the sun being inversely as the



N. WINTER SOLSTICE IN APHELION. N. WINTER SOLSTICE IN PERIHELION.

FIG. 1.—ECCENTRICITY OF THE EARTH'S ORBIT IN RELATION TO CLIMATE.

square of the distance, it follows that the amount of heat received by the earth in these two positions will be as 19 to 26. The present eccentricity being ·0168, the earth's distance during our northern winter is 90,847,680 miles. Suppose now that, from the precession of the equinoxes, winter in our northern hemisphere should happen when the earth is in the aphelion of its orbit, at the time that the orbit is at its greatest eccentricity; the earth would then be 8,736,420 miles farther from the sun in winter than it is at present. The direct heat of the sun would therefore, during winter, be one-fifth less and during summer one-fifth greater than now. This enormous difference would necessarily affect the climate to a very great extent. Were the winters under these circumstances to occur

when the earth was in the perihelion of its orbit, the earth would then be 14,368,200 miles nearer the sun in winter than in summer. In this case the difference between winter and summer in our latitudes would be almost annihilated. But as the winters in the one hemisphere correspond with the summers in the other, it follows that while the one hemisphere would be enduring the greatest extremes of summer heat and winter cold, the other would be enjoying perpetual summer.

"It is quite true that whatever may be the eccentricity of the earth's orbit, the two hemispheres must receive equal quantities of heat per annum; for proximity to the sun is exactly compensated by the effect of swifter motion. The total amount of heat received from the sun between the two equinoxes is therefore the same in both halves of the year, whatever the eccentricity of the earth's orbit may be. For example, whatever extra heat the southern hemisphere may at present receive per day from the sun during its summer months, owing to greater proximity to the sun, is exactly compensated by a corresponding loss arising from the shortness of the season; and, on the other hand, whatever deficiency of heat we in the northern hemisphere may at present have per day during our summer half-year, in consequence of the earth's distance from the sun, is also exactly compensated by a corresponding length of season.

"It is well known, however, that those simple changes in the sun's summer and winter distances would not alone produce a glacial epoch, and that physicists, confining their attention to the purely astronomical effects, were perfectly correct in affirming that no increase of eccentricity of the earth's orbit could account for that epoch. But the important fact was overlooked that, although the glacial epoch could not result directly from an increase of eccentricity, it might nevertheless do so indirectly from physical agents that were brought into operation as a result of an increase of eccentricity. The following is an outline of what these physical agents were, how they were brought into operation, and the way in which they may have led to the glacial epoch.

"With the eccentricity at its superior limit and the winter occurring in the aphelion, the earth would, as we have seen, be 8,736,420 miles farther from the sun during that season than at present. The reduction in the amount of heat received from the sun, owing to his increased distance, would lower the midwinter temperature to an enormous extent. In temperate regions the greater portion of the moisture of the air is at present precipitated in the form of rain, and the very small portion which falls as snow disappears in the course of a few weeks at most. But in the circumstances under consideration, the mean winter temperature would be lowered so much below the freezing-point that what now falls as rain during that season would then fall as snow. This is not all; the winters would then not only be colder than now, but they would also be much longer. At present the winters are nearly eight days shorter than the

summers; but with the eccentricity at its superior limit and the winter solstice in aphelion, the length of the winters would exceed that of the summers by no fewer than thirty-six days. The lowering of the temperature and the lengthening of the winter would both tend to the same effect, viz., to increase the amount of snow accumulated during the winter; for, other things being equal, the larger the snow-accumulating period the greater the accumulation. It may be remarked, however, that the absolute quantity of heat received during winter is not affected by the decrease in the sun's heat,[1] for the additional length of the season compensates for this decrease. As regards the absolute amount of heat received, increase of the sun's distance and lengthening of the winter are compensatory, but not so in regard to the amount of snow accumulated. The consequence of this state of things would be that, at the commencement of the short summer, the ground would be covered with the winter's accumulation of snow. Again, the presence of so much snow would lower the summer temperature, and prevent to a great extent the melting of the snow.

"There are three separate ways whereby accumulated masses of snow and ice tend to lower the summer temperature, viz.:—

"*First*, By means of direct radiation. No matter what the intensity of the sun's rays may be, the temperature of snow and ice can never rise above 32°. Hence the presence of snow and ice tends by direct radiation to lower the temperature of all surrounding bodies to 32°. In Greenland, a country covered with snow and ice, the pitch has been seen to melt on the side of a ship exposed to the direct rays of the sun, while at the same time the surrounding air was far below the freezing point; a thermometer exposed to the direct radiation of the sun has been observed to stand above 100°, while the air surrounding the instrument was actually 12° below the freezing-point. A similar experience has been recorded by travellers on the snow-fields of the Alps. These results, surprising as they no doubt appear, are what we ought to expect under the circumstances. Perfectly dry air seems to be nearly incapable of absorbing radiant heat. The entire radiation passes through it almost without any sensible absorption. Consequently the pitch on the side of the ship may be melted, or the bulb of the thermometer raised to a high temperature by the direct rays of the sun, while the surrounding air remains intensely cold. The air is cooled by *contact* with the snow-covered ground, but is not heated by the radiation from the sun.

"When the air is charged with aqueous vapour, a similar cooling effect also takes place, but in a slightly different way. Air charged with aqueous vapour is a good absorber of radiant heat, but it can only absorb those rays which agree with it in *period*. It so happens

[1] When the eccentricity is at its superior limit, the absolute quantity of heat received by the earth during the year is, however, about one three-hundredth part greater than at present. But this does not affect the question at issue.

that rays from snow and ice are, of all others, those which it absorbs best. The humid air will absorb the total radiation from the snow and ice, but it will allow the greater part of, if not nearly all, the sun's rays to pass unabsorbed. But during the day, when the sun is shining, the radiation from the snow and ice to the air is negative; that is, the snow and ice cool the air by radiation. The result is, the air is cooled by radiation from the snow and ice (or rather, we should say, *to* the snow and ice) more rapidly than it is heated by the sun; and as a consequence, in a country like Greenland, covered with an icy mantle, the temperature of the air, even during summer, seldom rises above the freezing-point. Snow is a good reflector, but as simple reflection does not change the character of the rays, they would not be absorbed by the air, but would pass into stellar space. Were it not for the ice, the summers of North Greenland, owing to the continuance of the sun above the horizon, would be as warm as those of England; but instead of this, the Greenland summers are colder than our winters. Cover India with an ice sheet, and its summers would be colder than those of England.

"*Second*, Another cause of the cooling effect is that the rays which fall on snow and ice are to a great extent reflected back into space. But those that are not reflected, but absorbed, do not raise the temperature, for they disappear in the mechanical work of melting the ice. For whatsoever may be the intensity of the sun's heat, the surface of the ground will be kept at 32° so long as the snow and ice remain unmelted.

"*Third*, Snow and ice lower the temperature by chilling the air and condensing the vapour into thick fogs. The great strength of the sun's rays during summer, due to his nearness at that season, would, in the first place, tend to produce an increased amount of evaporation. But the presence of snow-clad mountains and an icy sea would chill the atmosphere and condense the vapour into thick fogs. The thick fogs and cloudy sky would effectually prevent the sun's rays from reaching the earth, and the snow, in consequence, would remain unmelted during the entire summer. In fact, we have this very condition of things exemplified in some of the islands of the Southern Ocean at the present day. Sandwich Land, which is in the same parallel of latitude as the north of Scotland, is covered with ice and snow the entire summer; and in the island of South Georgia, which is in the same parallel as the centre of England, the perpetual snow descends to the very sea-beach. Captain Sir James Ross found the perpetual snow at the sea-level at Admiralty Inlet, South Shetland, in lat. 64°; and while near this place the thermometer in the very middle of summer fell at night to 23° F. The reduction of the sun's heat and lengthening of the winter, which would take place when the eccentricity is near to its superior limit and the winter in aphelion, would in this country produce a state of things perhaps as bad as, if not worse than, that which at present exists in South Georgia and South Shetland.

"The cause which above all others must tend to produce great changes of climate, is the deflection of great ocean currents. A high condition of eccentricity tends, we have seen, to produce an accumulation of snow and ice on the hemisphere whose winters occur in aphelion. The accumulation of snow in turn tends to lower the summer temperature, cut off the sun's rays, and retard the melting of the snow. In short, it tends to produce on that hemisphere a state of glaciation. Exactly opposite effects take place on the other hemisphere, which has its winter in perihelion. There the shortness of the winters, combined with the high temperature arising from the nearness of the sun, tends to prevent the accumulation of snow. The general result is that the one hemisphere is cooled and the other heated. This state of things now brings into play the agencies which lead to the deflection of the Gulf Stream and other great ocean currents.

"Owing to the great difference between the temperature of the equator and the poles, there is a constant flow of air from the poles to the equator. It is to this that the trade-winds owe their existence. Now, as the strength of these winds will, as a general rule, depend upon the difference of temperature that may exist between the equator and higher latitudes, it follows that the trades on the cold hemisphere will be stronger than those on the warm. When the polar and temperate regions of the one hemisphere are covered to a large extent with snow and ice, the air, as we have just seen, is kept almost at the freezing-point during both summer and winter. The trades on that hemisphere will, of necessity, be exceedingly powerful; while on the other hemisphere, where there is comparatively little snow or ice, and the air is warm, the trades will consequently be weak. Suppose now the northern hemisphere to be the cold one. The north-east trade-winds of this hemisphere will far exceed in strength the south-east trade-winds of the southern hemisphere. The *median line* between the trades will consequently lie to a very considerable distance to the south of the equator. We have a good example of this at the present day. The difference of temperature between the two hemispheres at present is but trifling to what it would be in the case under consideration; yet we find that the south-east trades of the Atlantic blow with greater force than the north-east trades, sometimes extending to 10° or 15° N. lat., whereas the north-east trades seldom blow south of the equator. The effect of the northern trades blowing across the equator to a great distance will be to impel the warm water of the tropics over into the Southern Ocean. But this is not all; not only would the median line of the trades be shifted southwards, but the great equatorial currents of the globe would also be shifted southwards.

"Let us now consider how this would affect the Gulf-stream. The South American continent is shaped somewhat in the form of a triangle, with one of its angular corners, called Cape St. Roque, pointing eastwards. The equatorial current of the Atlantic impinges

against this corner; but as the greater portion of the current lies a little to the north of the corner, it flows westward into the Gulf of Mexico and forms the Gulf-stream. A considerable portion of the water, however, strikes the land to the south of the cape, and is deflected along the shore of Brazil into the Southern Ocean, forming what is known as the Brazilian current. Now, it is obvious that the shifting of the equatorial current of the Atlantic only a few degrees to the south of its present position—a thing which would certainly take place under the conditions which we have been detailing—would turn the entire current into the Brazilian branch, and instead of flowing chiefly into the Gulf of Mexico, as at present, it would all flow into the Southern Ocean, and the Gulf-stream would consequently be stopped. The stoppage of the Gulf-stream, combined with all those causes which we have just been considering, would place Europe under a glacial condition, while at the same time the temperature of the Southern Ocean would, in consequence of the enormous quantity of warm water received, have its temperature (already high from other causes) raised enormously. And what holds true in regard to the currents of the Atlantic holds also true, though perhaps not to the same extent, of the currents of the Pacific.

"If the breadth of the Gulf-stream be taken at 50 miles, its depth at 1000 feet, its mean velocity at 2 statute miles an hour, the temperature of the water when it leaves the Gulf at 65°, and the return current at 40° F.,[1] then, as has been shown in *Climate and Time*, chapter ii., the quantity of heat conveyed into the Atlantic by this stream is equal to one-fourth of all the heat received from the sun by that ocean from the Tropic of Cancer to the Arctic Circle.[2] From principles discussed at considerable length in *Climate and Time*, it is shown that, but for the Gulf-stream and other currents, London would have a mean annual temperature 40° lower than at present.

"But there is still another cause which must be noticed:—a strong undercurrent of air *from* the north implies an equally strong upper current *to* the north. Now if the effect of the undercurrent would be to impel the warm water at the equator to the south, the effect of the upper current would be to carry the aqueous vapour formed at the equator to the north; the upper current, on reaching the snow and ice of temperate regions, would deposit its moisture in the form of snow; so that it is probable that, notwithstanding the great cold of the glacial epoch, the quantity of snow falling in the northern region would be enormous. This would be particularly the case during summer, when the earth would be in the perihelion and

[1] Sir Wyville Thomson states that in May, 1873, the *Challenger* expedition found the Gulf-stream, at the point where it was crossed, to be about sixty miles in width, 100 fathoms deep, and flowing at the rate of three knots per hour. This makes the volume of the stream one-fifth greater than the above estimate.

[2] The quantity of heat conveyed by the Gulf-stream for distribution is equal to 77, 479,650,000,000,000,000 foot-pounds per day. The quantity received from the sun by the North Atlantic is 310,923,000,000,000,000,000 foot-pounds.

the heat at the equator great. The equator would be the furnace where evaporation would take place, and the snow and ice of temperate regions would act as a condenser.

"The foregoing considerations, as well as many others which might be stated, lead to the conclusion that, in order to raise the mean temperature of the globe, *water* should be placed along the equator, and not *land*, as was contended by Sir Charles Lyell and others. For if land be placed at the equator, the possibility of conveying the sun's heat from the equatorial regions by means of ocean currents is prevented."[1]

Inter-Glacial Periods.—Allusion has already been made to the accumulating evidence that changes of climate have been recurrent, and to the deduction from this alternation or periodicity that they have probably been due to some general or cosmical cause. Dr. Croll has ingeniously shown that every long cold period arising in each hemisphere from the circumstances sketched in the preceding pages, must have been interrupted by several shorter warm periods. "When the one hemisphere," he says, "is under glaciation, the other is enjoying a warm and equable climate. But, owing to the precession of the equinoxes, the condition of things on the two hemispheres must be reversed every 10,000 years or so. When the solstice passes the aphelion, a contrary process commences; the snow and ice gradually begin to diminish on the cold hemisphere and to make their appearance on the other hemisphere. The glaciated hemisphere turns by degrees warmer, and the warm hemisphere colder, and this continues to go on for a period of ten or twelve thousand years, until the winter solstice reaches the perihelion. By this time the conditions of the two hemispheres have been reversed; the formerly glaciated hemisphere has now become the warm one, and the warm hemisphere the glaciated. The transference of the ice from the one hemisphere to the other continues as long as the eccentricity remains at a high value. It is probable that, during the warm inter-glacial periods, Greenland and the Arctic regions would be comparatively free from snow and ice, and enjoying a temperate and equable climate."

[1] That climate, however, may be considerably affected by changes, such as are known to have taken place in the distribution of land and sea, must be frankly conceded. This has been recently cogently argued by Mr. Wallace in his "Island Life," 1880.

BOOK II.

GEOGNOSY.

AN INVESTIGATION OF THE MATERIALS OF THE EARTH'S SUBSTANCE.

PART I.—A GENERAL DESCRIPTION OF THE PARTS OF THE EARTH.

A DISCUSSION of the geological changes which our planet has undergone, ought to be preceded by a study of the materials of which the planet consists. This latter branch of inquiry is termed Geognosy.

Viewed in a broad way, the earth may be considered as consisting of (1) two envelopes,—an outer one of gas completely surrounding the planet, and an inner one of water covering about three-fourths of the globe; and (2) a globe, cool and solid on its surface, but possessing a high internal temperature.

I.—*The Envelopes.*

It is certain that the present gaseous and liquid envelopes of the planet form only a portion of the original mass of gas and water with which the globe was invested. Fully a half of the outer shell or crust of the earth consists of oxygen, which there can be no doubt once existed in the atmosphere. The extent likewise to which water has been abstracted by minerals is almost incredible. It has been estimated that already one-third of the whole mass of the ocean has been thus absorbed. Eventually the condition of the planet will probably resemble that of the moon—a globe without air or water or life of any kind.

1. The Atmosphere.—The gaseous envelope to which the name of atmosphere is given extends at least to a distance of 40 or 45 miles from the earth's surface, perhaps in a state of extreme tenuity to a much greater height. But its thickness must necessarily vary with latitude and changes in atmospheric pressure. The layer of air lying over the poles is not so deep as that which surrounds the equator.

Many speculations have been made regarding the chemical composition of the atmosphere during former geological periods. There can indeed be no doubt that it must originally have differed very greatly from its present condition. Besides the abstraction of the oxygen which now forms fully a half of the outer crust of

the earth, the vast beds of coal found all over the world, in geological formations of many different ages, doubtless represent so much carbon dioxide once present in the air. The chlorides in the sea likewise were probably carried down out of the atmosphere in the primitive condensation of aqueous vapour. It has often been suggested that during the Carboniferous period the atmosphere must have been warmer and with more aqueous vapour and carbon dioxide in its composition than at the present day, to admit of so luxuriant a flora as that from which the coal-seams were formed. There seems, however, to be at present no method of arriving at any certainty on this subject.

As now existing, the atmosphere is considered to be normally a mechanical mixture of nearly 4 volumes of nitrogen and 1 of oxygen (N 79·4, O 20·6), with minute proportions of carbon dioxide (carbonic acid) and water-vapour and still smaller quantities of ammonia and the powerful oxidising agent ozone. These quantities are liable to some variation according to locality. The mean proportion of carbon dioxide is about 4 parts in every 10,000 of air. In the air of streets and houses the proportion of oxygen diminishes, while that of carbon dioxide increases. According to the minute researches of Dr. Angus Smith, very pure air should contain not less than 20·99 per cent. of oxygen, with 0·030 of carbon dioxide; but he found impure air in Manchester to have only 20·21 of oxygen, while the proportion of carbon dioxide in that city during fog was ascertained to rise sometimes to 0·0679, and in the pit of the theatre to the very large amount of 0·2734. Small as the percentage of carbon dioxide in ordinary air may seem, yet the total amount of this gas in the whole atmosphere probably exceeds what would be disengaged if all the vegetable and animal matter on the earth's surface were burnt.

The other substances in the air are gases, vapours, and solid particles. Of these by much the most important is the vapour of water, which is always present, but in very variable amount according to temperature.[1] It is this vapour which condenses into dew, rain, hail, and snow. In assuming a visible form, and descending through the atmosphere, it takes up a minute quantity of air, and of the different substances which the air may contain. Being caught by the rain, and held in solution or suspension, these substances can be best examined by analysing rain-water. In this way the atmospheric gases, ammonia, nitric, sulphurous, and sulphuric acids, chlorides, various salts, solid carbon, inorganic dust, and organic matter have been detected. To the fine microscopic dust so abundant in the air, great importance in the condensation of vapour has recently been assigned. (Book III. Part II. Section ii.)

[1] A cubic metre of air at the freezing point can hold only 4·871 grammes of water-vapour, but at 40° C. can take up 50·70 grammes. One cubic mile of air saturated with vapour at 35° C. will if cooled to 0° deposit upwards of 140,000 tons of water as rain. Roscoe and Schorlemmer's "Chemistry," i. p. 452.

The comparatively small but by no means unimportant proportions of these minor components of the atmosphere are much more liable than the more essential gases to variations. Chloride of sodium, for instance, is, as might be expected, particularly abundant in the air bordering the sea. Nitric acid, ammonia, and sulphuric acid appear in the air of towns most conspicuously. The organic substances present in the air are sometimes living germs, such as probably often lead to the propagation of disease, and sometimes mere fine particles of dust derived from the bodies of living or dead organisms.[1]

As a geological agent the atmosphere effects changes by the chemical reactions of its constituent gases and vapours, by its varying temperature, and by its motions. Its functions in these respects are described in Book III. Part II. Section i.

2. **The Oceans.**—About three-fourths of the surface of the globe (or about 144,712,000 square miles) are covered by the irregular sheet of water known as the Sea. Within the last ten years much new light has been thrown upon the depths, temperatures, and biological conditions of the ocean-basins, more particularly by the *Lightning*, *Porcupine*, and *Challenger*, expeditions fitted out by the British Government. It has been ascertained that few parts of the Atlantic Ocean exceed 3000 fathoms, the deepest sounding obtained there being one taken about 100 miles north from the island of St. Thomas, which gave 3875 fathoms, or rather less than 4½ miles. The Atlantic appears to have an average depth in its more open parts of from 2000 to 3000 fathoms, or from about 2 to 3½ miles. In the Pacific Ocean the *Challenger* got soundings of 3950 and 4475 fathoms, or about 4½ and rather more than 5 miles. But these appear to mark exceptionally abysmal depressions, the average depth being, as in the Atlantic, between 2000 and 3000 fathoms. We may therefore assume, as probably not far from the truth, that the average depth of the ocean is about 2,500 fathoms, or nearly 3 miles. Its total cubic contents will thus be about 400 millions of cubic miles.

With regard also to the form of the great ocean bottoms, much additional information has recently been obtained. Over vast areas in the central regions of the sea, the floor appears to form great plains with comparatively few inequalities, but with lines of submarine ridges comparable to chains of hills or mountains on the land. The crests of some of these ridges rise above the sea-level, as in the remarkable line of islands in the south-western region of the Pacific Ocean. It is significant that the islands which thus appear far from

[1] The air of towns is peculiarly rich in impurities, especially in manufacturing districts, where much coal is used. These impurities, however, though of serious consequence to the towns in a sanitary point of view, do not sensibly affect the general atmosphere, seeing that they are probably in great measure taken out of the air by rain, even in the districts which produce them. They possess, however, a special geological significance, and in this respect, too, have important economic bearings. See on this whole subject, Dr. Angus Smith's *Air and Rain*.

any large mass of land are of volcanic origin and contain no ancient formations. St. Helena and Ascension in the Atlantic, and the Friendly and Sandwich Islands in the Pacific Ocean are conspicuous examples.

The water of the oceans is distinguished from ordinary terrestrial waters by a higher specific gravity, and the presence of so large a proportion of saline ingredients as to impart a strongly salt taste. The average density of sea-water is about 1·026, but it varies slightly in different parts even of the same ocean. According to the recent observations of Mr. J. Y. Buchanan during the *Challenger* expedition, some of the heaviest sea-water occurs in the pathway of the trade-winds of the North Atlantic, where evaporation must be comparatively rapid, a density of 1·02781 being registered. Where, however, large rivers enter the sea, or where there is much melting ice, the density diminishes; Mr. Buchanan found among the broken ice of the Antarctic Ocean that it had sunk to 1·02418.[1]

The greater density of sea-water depends of course upon the salts which it contains in solution. At an early period in the earth's history the water now forming the ocean, together with the rivers, lakes and snowfields of the land, existed as vapour, in which were mingled many other gases and vapours, the whole forming a vast atmosphere surrounding the still intensely hot globe. Under the enormous pressure of the primæval atmosphere the first condensed water might have had the temperature of a dull red heat.[2] In condensing, it would carry down with it many substances in solution. The salts now present in sea-water are to be regarded as principally derived from the primeval constitution of the sea, and thus we may infer that the sea has always been salt. It is also probable that, as in the case of the atmosphere, the composition of the ocean water has acquired its present character only after many ages of slow change, and the abstraction of much mineral matter originally contained in it. There is evidence indeed among the geological formations that large quantities of lime, silica, chlorides, and sulphates have in the course of time been removed from the sea.[3]

But it is manifest also that, whatever may have been the original composition of the oceans, they have for a vast section of geological time been constantly receiving mineral matter in solution from the land. Every spring, brook, and river removes various salts from the rocks over which it moves, and these substances, thus dissolved, eventually find their way into the sea. Consequently sea-water ought to contain more or less traceable proportions of every substance which the terrestrial waters can remove from the land, in short, of probably every element present in the outer shell of the globe, for there seems to be no constituent of the earth which may not, under

[1] Buchanan, *Proc. Roy. Soc.* (1876), vol. xxiv.

[2] *Q. J. Geol. Soc.* xxxvi. (1880) pp. 112, 117.

[3] Dr. Sterry Hunt even supposes that the saline waters of Canada and the northern States derive their mineral ingredients from the salts still retained among the sediments and precipitates of the ancient sea in which the earlier Palæozoic rocks were deposited. —*Geological and Chemical Essays*, p. 104.

certain circumstances, be held in solution in water. Moreover, unless there be some counteracting process to remove these mineral ingredients, the ocean water ought to be growing, insensibly perhaps, salter, for the supply of saline matter from the land is incessant. It has been ascertained indeed, with some approach to certainty, that the salinity of the Baltic and Mediterranean is gradually increasing.[1]

The average proportion of saline constituents in the water of the great oceans far from land is about three and a half parts in every hundred of water. But in enclosed seas, receiving much fresh water, it is greatly reduced, while in those where evaporation predominates it is correspondingly augmented. Thus the Baltic water contains from one-seventh to nearly a half of the ordinary proportion in ocean water, while the Mediterranean contains sometimes one-sixth more than that proportion. Forchhammer has shown the presence of the following twenty-seven elements in sea-water: oxygen, hydrogen, chlorine, bromine, iodine, fluorine, sulphur, phosphorus, nitrogen, carbon, silicon, boron, silver, copper, lead, zinc, cobalt, nickel, iron, manganese, aluminium, magnesium, calcium, strontium, barium, sodium, and potassium.[2] To these may be added arsenic, lithium, caesium, rubidium, gold, and probably still other elements. A variable proportion of organic matter is always present. The chief mineral constituents occur in the following average ratios:—

	Percentage.
Sodium chloride (common salt)	75·786
Magnesium chloride	9·159
Potassium chloride	3·657
Calcium sulphate (gypsum)	4·617
Magnesium sulphate (Epsom salts)	5·597
Sodium bromide	1·184
	100·000
Total percentage of salts in sea-water	3·527

In addition to its salts sea-water always contains dissolved atmospheric gases. From the researches conducted during the voyage of the *Bonité* in the Atlantic and Indian Oceans it was estimated that the gases in 100 volumes of sea-water ranged from 1·85 to 3·04, or from two to three per cent. From observations made during the *Porcupine* cruise of 1868 it was inferred that the proportion of oxygen was greatest (25·1 per cent.) in the surface water, and least (19·5) in the bottom water, while that of carbonic acid was least at the top (20·7) and greatest (27·9) at the bottom, and that the action of the waves was partially to eliminate the latter gas and to increase the amount of oxygen. More recently, however, during the voyage of the *Challenger*, Mr. J. Y. Buchanan ascertained that the proportion of carbonic acid was always nearly the same for similar

[1] Paul, in Watts's *Dictionary of Chemistry*, v. p. 1020.

[2] Forchhammer, *Phil. Trans.* clv. p. 205. According to Thorpe and Morton (*Chem. Soc. Journ* xxiv. p. 506), the water of the Irish Sea contains in winter rather more salts than in summer, owing to diminished evaporation and a less supply of fresh water. These authors state that in 1000 grammes of the summer water of the Irish Sea they found 0·04754 gramme of carbonate of lime, 0·00503 of ferrous carbonate and traces of silicic acid.

temperatures, the amount in the Atlantic surface water, between 20° and 25° C., being 0·0466 gramme per litre, and in the surface Pacific water 0·0268. He points out the curious fact that, according to his analyses, sea-water contains sometimes at least thirty times as much carbonic acid as an equal bulk of fresh water would do, and he traces the greater power of absorption to the presence of the sulphates.[1]

II.—*The Solid Globe.*

Within the atmospheric and oceanic envelopes lies the inner solid globe. The only portion of it which rising above the sea is visible to us, and forms what we term Land, occupies about one-fourth of the total superficies of the globe, or about 52,000,000 square miles.

§ 1. **The Outer Surface.**—The land placed chiefly in the northern hemisphere is disposed in large masses, or continents, which taper southwards to about half the distance between the equator and the south pole. No adequate cause has yet been assigned for the present distribution of the land. It can be shown, however, that portions of the continents are of extreme geological antiquity. There is reason to believe, indeed, that the present terrestrial areas have on the whole been land, or have at least never been submerged beneath deep water from the time of the earliest stratified formations; and that, on the other hand, the ocean basins have always been vast areas of depression. This subject will be discussed in subsequent parts of this volume.

In the new world the continental trend is approximately north and south; in the old world, though less distinctly marked it ranges on the whole east and west. An intimate relation may be observed between this general trend and the direction of the mountain chains. This is best exhibited by the American continent. In the old world, Europe and Africa, though now disjoined, were once united, and may be considered as one continental mass. Europe and Asia, on the other hand, though now united were partially separated in comparatively recent geological times by a long inlet which extended for several hundred miles southward from the Arctic Ocean, and by the great Mediterranean Sea, of which the existing Black, Caspian, and Aral Seas are the shrunk remnants. Asia is linked with Australia by a great chain of islands; but there is no reason to suppose that the relation was ever closer than it is now. On the contrary, the great contrast between the Asiatic and Australian faunas affords good grounds for the belief, that at least for an enormous period of time Asia and Australia have been divided by an important barrier of sea.

While any good map of the globe enables us to see at a glance the relative position and area of the continents and oceans, most maps fail to furnish any data by which the general height or volume of a continent may be estimated. As a rule, the mountain chains are exaggerated in breadth, and incorrectly indicated, while no attempt is made to distinguish between high plateaux and low plains. In

[1] *Proc. Roy. Soc.* xxiv.

North America, for example, a continuous shaded ridge is placed down the axis of the continent and marked "Rocky Mountains," while the vast level or gently rolling prairies are left with no mark to distinguish them from the maritime plains of the eastern and southern states. In reality there is no such continuous mountain chain. The so-called "Rocky Mountains" consist of many independent, and sometimes widely separate ridges, having a general meridional trend rising above a vast plateau, which is itself 4000 or 5000 feet in elevation. It is not these intermittent ridges which really form the great mass of the land in that region, but the widely extended lofty plateau, or rather succession of plateaux, which supports them. In Europe also the Alps form but a subordinate part of the total bulk of the land. If their materials could be spread out over the continent, it has been calculated that they would not increase its height more than about twenty-one feet.

Attempts have been made to estimate the probable average height which would be attained if the various inequalities of the land could be levelled down. Humboldt estimated that the mean height of Europe must be about 671, of Asia 1132, of North America 748, and of South America 1151 feet.[1] Herschel supposed the mean height of Africa to be 1800 feet.[2] These figures, though based on the best data available at the time, are probably not very near the truth. In particular, the average height assigned to North America is evidently less than it should be; for the great plains west of the Mississippi valley reach an altitude of about 5000 feet, and serve as the platform from which the mountain ranges rise. Recent calculations by G. Leipoldt give for the mean height of Europe 296·838 metres (973·628 feet).[3] It is very desirable that more reliable estimates should now be made for the whole globe, as furnishing a means of comparison between the relative bulk of different continents, and the amount of material on which geological changes can be effected.

The highest elevation of the surface of the land is the summit of Mount Everest, in the Himalaya range (29,002 feet); the deepest depression not covered by water is that of the shores of the Dead Sea (1300 feet below sea-level). There are, however, many subaqueous portions of the land which sink to far greater depths. The bottom of the Caspian Sea, for instance, lies about 3000 feet below the general sea-level.

There are two conspicuous junction-lines of the land with its overlying and surrounding envelopes. First, with the Air, expressed by the contours or relief of the land. Second, with the Sea, expressed by coast-lines.

[1] *Asie Centrale*, tom. 1, p. 168.

[2] *Physical Geography*, p. 119.

[3] *Die Mittlere Höhe Europas*, Leipzig, 1874. In this work the mean height of Switzerland is put down as 1299·91 metres; Austria, 517·87; Italy, 517·17; Scandinavia, 428·10; France, 393·84; Great Britain, 217·70; German Empire, 213·66; Russia, 167·09; Belgium, 163·36; Denmark (exclusive of Iceland), 35·20; the Netherlands (exclusive of Luxembourg and the tracts below sea-level), 9·61.

(1) Contours or Relief of the Land.—While the surface of the land presents endless diversities of detail, its leading features may be generalised under the designations of mountains, table-lands, and plains.

Mountains.—The word "mountain" is, properly speaking, not a scientific term. It includes many forms of ground utterly different from each other in size, shape, structure, and origin. It is popularly applied to any considerable eminence or range of heights, but the height and size of the elevated ground so designated vary indefinitely. In a really mountainous country the word would be restricted to the loftier masses of ground, while such a word as hill would be given to the lesser heights. But in a region of low or gently undulating land, where any conspicuous eminence becomes important, the term mountain is lavishly used. In Eastern America this habit has been indulged in to such an extent, that what are, so to speak, mere hummocks in the general landscape, are dignified by the name of mountains.

It is hardly possible to give a precise scientific definition to a term so vaguely employed in ordinary language. When a geologist uses the word, he must either be content to take it in its familiar vague sense, or must add some phrase defining the meaning which he attaches to it. He finds that there are three leading and totally distinct types of elevation which are all popularly termed mountains. 1. Single eminences standing alone upon a plain or table-land. This is essentially the volcanic type. The huge cones of Vesuvius, Etna, and Teneriffe, as well as the smaller ones so abundant in volcanic districts, are examples of it. There occur, however, occasional isolated eminences that stand up as remnants of once extensive rock-formations. These have no real analogy with volcanic elevations, but should be classed under the next type. The remarkable *buttes* of Western America are good illustrations of them. 2. Groups of eminences connected at the sides or base, often forming lines of ridge between divergent valleys, and owing their essential forms not to underground structure so much as to superficial erosion. Many of the more ancient uplands both in the Old World and the New furnish examples of this type, such as the Highlands of Scotland, the hills of Cumberland and Wales, the high grounds between Bohemia and Bavaria, the Laurentide Mountains of Canada, and the Green and White Mountains of New England. 3. Lines of lofty ridge rising into a succession of more or less distinct summits, their general external form having relation to an internal plication of their component rocks. These linear elevations, where their existence and trend have been determined immediately by subterranean movement, are the true mountain-ranges of the globe. They may be looked upon as the crests of the great waves into which the crust of the earth has been thrown. All the great mountain lines of the world belong to this type.

Leaving the details of mountain form to be described in Book VII., we may confine our attention here to a few of the more important

general features. In elevations of the third or true mountain type, there may be either one line or range of heights, or a series of parallel and often coalescent ranges. In the Western Territories of the United States, the vast plateau has been as it were wrinkled by the uprise of long intermittent ridges, with broad plains and basins between them. Each of these forms an independent mountain range. In the heart of Europe, the Bernese Oberland, the Pennine, Lepontine, Rhaetic, and other ranges form one great Alpine chain or system.

In a great mountain chain such as the Alps, Himalayas, or Andes, there is one general persistent trend for the successive ridges. Here and there lateral offshoots may diverge, but the dominant direction of the axis of the main chain is generally observed by its component ridges until they disappear. Yet while the general parallelism is preserved, no single range may be traceable for more than a comparatively short distance; it may be found to pass insensibly into another, while a third may be seen to begin on a slightly different line, and to continue with the same dominant trend until it in turn becomes confluent. The various ranges are thus apt to assume an arrangement *en échelon*.

The ranges are separated by *longitudinal* valleys, that is, depressions coincident with the general direction of the chain. These, though sometimes of great length, are relatively of narrow width. The valley of the Rhône, from the source of the river down to Martigny, offers an excellent example. By a second series of valleys the ranges are trenched, often to a great depth, and in a direction transverse to the general trend. The Rhône furnishes also an example of one of these *transverse* valleys, in its course from Martigny to the Lake of Geneva. In most mountain regions the heads of two adjacent transverse valleys are connected by a depression or *pass* (*col*, *joch*).

A large block of mountain ground, rising into one or more dominant summits, and more or less distinctly defined by longitudinal and transverse valleys, is termed in French a *massif*—a word for which there is no good English equivalent. Thus in the Swiss Alps we have the massifs of the Glärnisch, the Tödi, the Matterhorn, the Jungfrau, &c.

Very exaggerated notions are common regarding the angle of declivity in mountains. Sections drawn across any mountain or mountain-chain on a true scale, that is, with the length and height on the same scale, bring out the fact that even in the loftiest mountains the breadth of base is always very much greater than the height. Actual vertical precipices are less frequent than is usually supposed, and even when they do occur, form but incidents in the general declivity of mountains. Angles of slope more than 30° are likewise far less abundant than casual tourists believe. Even such steep declivities as those of 38° or 40° are most frequently found as *talus*-slopes at the foot of crumbling cliffs, and represent the angle of repose of the disintegrated débris. Here and there, where the blocks loosened by weathering are of large size, they may accumulate upon each other in such a manner that for short distances the

average angle of declivity may mount as high as 65°. But such steep slopes are of limited extent. Declivities exceeding 40°, and bearing a large proportion to the total dimensions of hill or mountain, are always found to consist of naked rock. In estimating angles of inclination from a distance, the student will learn by practice how apt is the eye to be deceived by perspective and to exaggerate the true declivity, sometimes to mistake a horizontal for a highly inclined or vertical line. The mountain outline shown in Fig. 2 presents a slope of 25° between *a* and *b*, of 45° between *b* and *c*, of 17° between *c* and *d*, of 40° between *d* and *e*, and of 70° between *e* and *f*.

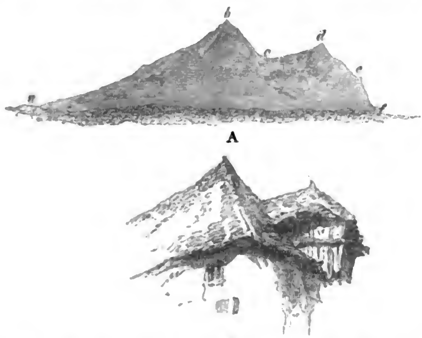


FIG. 2.—ANGLES OF SLOPE WHERE THE EYE MAY BE DECEIVED BY PERSPECTIVE. (AFTER RUSKIN.) A, MOUNTAIN OUTLINE; B, THE SAME OUTLINE AS SHOWN BY A COTTAGE ROOF.

FIG. 3.—SECTION FROM THE JURA TO MONT BLANC, ON THE SAME SCALE FOR LENGTH AND HEIGHT. *j*, JURA; *s*, LAKE OF GENEVA; *v*, VOIRONS; *m*, MOLE; *a*, AIGUILLE DE VARENS; *b*, BREVEN; M B, MONT BLANC.

At a great distance, or with bad conditions of atmosphere, these might be believed to be the real declivities. Yet if the same angles be observed in another way (as on a cottage roof at B), we may learn that an apparently inclined surface may really be horizontal[1] (as from *a* to *b* and from *c* to *d*), and that by the effect of perspective, slopes may be made to appear much steeper than they really are.

Much evil has resulted in geological research from the use of exaggerated angles of slope in sections and diagrams. It is therefore desirable that the student should from the beginning accustom himself to the drawing of outlines as nearly as possible on a true scale. The accompanying section of the Alps by De la Beche (Fig. 3) is of interest in this respect as one of the earliest illustrations

[1] Mr. Ruskin has well illustrated this point. See *Modern Painters*, vol. iv. p. 183, whence the illustrations in the text are taken.

of the advantage of constructing geological sections on a true scale as to the relative proportions of height and length.[1]

Table-lands or *Plateaux* are elevated regions of flat or undulating country, rising to heights of 1000 feet and upwards above the level of the sea. They are sometimes bordered with steep slopes, which descend from their edges, as the table-land of the Spanish peninsula does into the sea. In other cases they gradually sink into the plains and have no definite boundaries; thus the prairie land west of the Missouri slowly and imperceptibly ascends until it becomes a vast plateau from 4000 to 5000 feet above the sea. Occasionally a high table-land is encircled with lofty mountains, as in those of Quito and Titicaca among the Andes, and that of the heart of Asia; or it forms in itself the platform on which lines of mountains stand, as in North America, where the ranges included within the Rocky Mountains reach elevations of from 10,000 to 14,000 feet above the sea, but not more than from 5000 to 10,000 feet above the table-land.

Two types of table-land structure may be observed. 1. Table-lands consisting of level or gently undulated sheets of rock, the general surface of the country corresponding with that of the stratification. The Rocky Mountain plateau is an example of this type, which may be called that of Deposit, for the flat strata have been equably upraised nearly in the position in which they were deposited. 2. Table-lands formed out of contorted, crystalline, or other rocks, which have been planed down by superficial agents. This type, where the external form is independent of geological structure, may be termed that of Erosion. The *fjelds* of Norway are portions of such a table-land. In proportion to its antiquity, a plateau is trenched by running water into systems of valleys, until in the end it may lose its plateau character and pass into the second type of mountain ground above described. This change has largely altered the ancient table-land of Scandinavia, as will be illustrated in Book VII.

Plains are tracts of lowland (under 1000 feet in height) which skirt the sea-board of the continents and stretch inland up the river valleys. The largest plain in the world is that which, beginning in the centre of the British Islands, stretches across Europe and Asia. On the west it is bounded by the ancient table-lands of Scandinavia, Scotland, and Wales on the one hand, and those of Spain, France, and Germany on the other. Most of its southern boundary is formed by the vast belt of high ground which spreads from Asia Minor to the east of Siberia. Its northern margin sinks beneath the waters of the Arctic Ocean. This vast region is divided into an eastern and western tract by the low chain of the Ural Mountains, south of which its general level sinks, until underneath the Caspian Sea it reaches a depression of about 3000 feet below sea-level. For several hundred miles southward from the Arctic Ocean traces of recent sea-shells are found in the superficial deposits. Similar

[1] *Sections and Views, illustrative of Geological Phenomena*, 1830. *Geol. Observer* p. 646.

evidence likewise exists around the Caspian and Black Seas. There is thus proof that large portions of the great plain of the old world comparatively recently formed part of the sea-floor.

Along the eastern sea-board of America lies a broad belt of low plains, which attain their greatest dimensions in the regions watered by the larger rivers. Thus they cover thousands of square miles on the north side of the Gulf of Mexico, and extend for hundreds of miles up the valley of the Mississippi. Almost the whole of the valleys of the Orinoco, Amazon and La Plata is occupied with vast plains.

It is evident, from their distribution along river-valleys, and on the areas between the base of high grounds and the sea, that plains are essentially areas of deposit. They are the tracts that have received the detritus washed down from the slopes above them, whether that detritus has originally accumulated on the land or below the sea. Their surface presents everywhere loose sandy, gravelly, or clayey formations, indicative of its comparatively recent subjection to the operation of running water.

(2) Coast-lines.—A mere inspection of a map of the globe brings before the mind the striking differences which the masses of land present in their line of junction with the sea. As a rule, the southern continents possess a more uniform unindented coast-line than the northern. It has been estimated that the ratios between area and coast-line among the different continents stand approximately as in the following table:—

Northern.	Europe has 1 geographical mile of coast-line to			143 square miles of surface.	
	North America	,,	,,	265	,,
	Asia, including the islands		,,	469	,,
Southern.	Africa	,,	,,	895	,,
	South America	,,	,,	434	,,
	Australia	,,	,,	332	,,

In estimating the relative potency of the sea and of the atmospheric agents of disintegration in the task of wearing down the land, it is evidently of great importance to take into account the amount of surface respectively exposed to their operations. Other things being equal, there is relatively more marine erosion in Europe than in North America. But we require also to consider the nature of the coast-line, whether flat and alluvial, or steep and rocky, or with some intermediate blending of these two characters. By attending to this point, we are soon led to observe such great differences in the character of coast-lines, and such an obvious relation to differences of geological structure on the one hand, and to diversities in the removal or deposit of material on the other, as to suggest that the present coast-lines of the globe cannot be aboriginal, but must be referred to the operation of geological agents still at work. This inference is amply sustained by more detailed investigation. While the general distribution of land and water must undoubtedly be assigned to terrestrial movements affecting the whole globe, the present actual coasts of the land have unquestionably been produced by local causes.

Headlands project from the land because for the most part they consist of rock which has been better able to withstand the shock of the breakers. Bays and creeks, on the other hand, have been cut by the waves out of less durable materials. Again, by the sinking of land, ranges of hills have become capes and headlands, while the valleys have passed into the condition of bays, inlets, or fjords. By the uprise of the sea-bottom, tracts of low alluvial ground have been added to the land.

Hence speculations as to the history of the elevation of the land, based merely upon inferences from the form of coast-lines as expressed upon ordinary maps, are apt to be of little value. To be of real service, they demand a careful scrutiny of the actual coast-lines, and an amount of geological investigation which would require long and patient toil for its accomplishment.

Passing from the mere external form of the land to the composition and structure of its materials, we may begin by considering the general density of the entire globe, computed from observations and compared with that of the outer and accessible portion of the planet. Reference has already been made to the comparative density of the earth among the other members of the solar system. In inquiries regarding the history of our globe, the density of the whole mass of the planet as compared with water—the standard to which the specific gravities of terrestrial bodies are referred—is a question of prime importance. Various methods have been employed for determining the earth's density. The deflection of the plumb-line on either side of a mountain of known structure and density, the time of oscillation of the pendulum at great heights, at the sea-level, and in deep mines, the comparative force of gravitation as measured by the torsion balance, have each been tried with the following various results:

Plumb-line experiments on Schiehallien (Maskelyne and Playfair) gave as the mean density of the earth	4·713
Do. on Arthur's Seat, Edinburgh (James)	5·316
Pendulum experiments on Mont Cenis (Carlini and Giulio) . .	4·950
Do. in Harton coal-pit, Newcastle (Airy)	6·565
Torsion balance experiments (Cavendish, 1798).	5·480
Do. do. (Reich, 1838)	5·49
Do. do. (Baily, 1843)	5·660
Do. do. (Cornu and Baille, 1872, 3) . . .	5·50–5·56

Though these observations are somewhat discrepant, we may feel satisfied that the globe has a mean density neither much more nor much less than 5·5; that is to say, it is five and a half times heavier than one of the same dimensions formed of pure water. Now the average density of the materials which compose the accessible portions of the earth is between 2·5 and 3; so that the mean density of the whole globe is about twice as much as that of its outer part. We might therefore infer that the inside consists of much heavier materials than the outside, and consequently that the mass of the planet must contain at least two dissimilar portions—an exterior lighter crust or rind, and an interior heavier nucleus. But the effect of pressure

must necessarily increase the specific gravity of the interior, as will be alluded to further on.

§ 2. **The Crust.**—It was formerly a prevalent belief that the exterior and interior of the globe differed from each other to such an extent that, while the outer parts were cool and solid, the vastly more enormous inner part being intensely hot was more or less completely fluid. Hence the term "crust" was applied to the external rind in the usual sense of that word. This crust was variously computed to be ten, fifteen, twenty, or more miles in thickness. In the accompanying diagram (Fig. 4), for example, the thick line forming the circle represents a relative thickness of 100 miles. There are so many proofs of enormous and wide-spread corrugation of the materials of the earth's outer layers, and such abundant traces of former volcanic action, that geologists have naturally regarded the doctrine of a thin crust over a liquid interior as necessary for the explanation of a large class of terrestrial phenomena. For reasons which will be afterwards given, however, this doctrine has been opposed by eminent physicists and

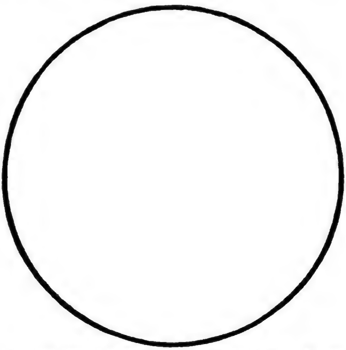


FIG. 4.—SUPPOSED CRUST OF THE EARTH, 100 MILES THICK.

is now abandoned by most geologists. Nevertheless the term "crust" continues to be used as a convenient word to denote those cool, upper, or outer layers of the earth's mass, in the structure and history of which, as the only portions of the planet accessible to human observation, lie the chief materials of geological investigation. The chemical and mineral constitution of the crust is fully discussed in later pages.

§ 3. **The Interior or Nucleus.**—Though the mere outside skin of our planet is all with which direct acquaintance can be expected, the irregular distribution of materials beneath the crust may be inferred from the present distribution of land and water, and the observed differences in the amount of deflection of the plumb-line near the sea and near mountain-chains. The fact that the southern hemisphere

is almost wholly covered with water appears explicable only on the assumption of an excess of density in the mass of that half of the planet. The existence of such a vast sheet of water as that of the Pacific Ocean is to be accounted for, says Archdeacon Pratt, by the presence of "some excess of matter in the solid parts of the earth between the Pacific Ocean and the earth's centre, which retains the water in its place, otherwise the ocean would flow away to the other parts of the earth." [1] The same writer points out that a deflection of the plumb-line towards the sea, which has in a number of cases been observed, indicates that "the density of the crust beneath the mountains must be less than that below the plains, and still less than that below the ocean-bed." [2] Apart therefore from the depressions of the earth's surface in which the oceans lie, we must regard the internal density, whether of crust or nucleus, to be somewhat irregularly arranged,—there being an excess of heavy materials in the water hemisphere and beneath the ocean-beds as compared with the continental masses.

It has been argued from the difference between the specific gravity of the whole globe and that of the crust, that the interior must consist of heavier material, and may be metallic. But the effect of the enormous internal pressure, it might be supposed, should make the density of the nucleus much higher, even if the interior consisted of matter which on the surface would be no heavier than that of the crust. In fact, we might on the contrary argue for the probable comparative lightness of the substance composing the nucleus. That the total density of the planet does not greatly exceed its observed amount may indicate that some antagonistic force counteracts the effects of pressure. The only force we can suppose capable of so acting is heat, though to what extent this counterbalancing takes place is still unknown. It must be admitted that we are still in ignorance of the law that regulates the compression of solids under such vast pressures as must exist within the earth's interior. We know that gases and vapours may be compressed into fluids, sometimes even into solids, and that in the fluid condition another law of compressibility begins. We know also from experiment that some substances have their melting point raised by pressure.[3] It may be that the same effect takes place within the earth; that pressure increasing inward to the centre of the globe, while augmenting the density of each successive shell, may retain the whole in a solid condition, yet at temperatures far above the normal melting points at the surface. Hence on this view of the matter it is possible that the difference between the density of the whole globe and that of the crust may be entirely due to pressure and not to any essential difference of

[1] *Figure of the Earth*, 4th edit., p. 236.

[2] *Op. cit.* p. 200. See also Herschel, *Phys. Geog.*; and O. Fisher, *Cambridge Phil. Trans.* xii., part ii.

[3] Under a pressure of 792 atmospheres, spermaceti has its melting point raised from 51° to 80·2°, and wax from 64·5° to 80·2°.

composition. Dr. Pfaff indeed offers a calculation to show that the mean terrestrial density of 5·5 is not incompatible with the notion that the whole globe consists of materials of the same density as the rocks of the crust.[1]

Analogies in the solar system, however, as well as the actual structure of the rocky crust of the globe, suggest that heavier metallic ingredients possibly predominate in the nucleus. If the materials of the globe were once, as they are believed to have been, in a fluid condition, they would then be subject to an internal arrangement in accordance with their relative specific gravities. We may conceive that as in the case of the sun, as well as of the solar system generally (*ante*, p. 8), there would be, so long as internal mobility lasted, a tendency in the denser elements to gravitate towards the centre, in the lighter to accumulate outside. That a distribution of this nature has certainly taken place to some extent is evident from the structure of the envelopes and crust. It is what might be expected if the constitution of the globe resembles on a small scale the larger planetary system of which it forms a part. The existence even of a metallic interior has been inferred from the metalliferous veins which traverse the crust, and which are commonly supposed to have been filled from below.[2]

Evidence of Internal Heat.—In the evidence obtainable as to the former history of the earth, no fact is of more importance than the existence of a high temperature beneath the crust, which has now been placed beyond all doubt. This feature of the planet's organization is made clear by the following proofs:—

(1.) *Volcanoes.*—In many regions of the earth's surface openings exist from which steam and hot vapours, ashes and streams of molten rock are from time to time emitted. The abundance and wide diffusion of these openings, inexplicable by any mere local causes, must be regarded as indicative of a very high internal temperature. If to the still active vents of eruption we add those which have formerly been the channels of communication between the interior and the surface, there are probably few large regions of the globe where proofs of volcanic action cannot be found. Everywhere we meet with masses of molten rock which have risen from below as if from some general reservoir. The phenomena of active volcanoes are fully discussed in Book III. Part I.

(2.) *Hot Springs.*—Where volcanic eruptions have ceased, evidence of a high internal temperature is still often to be found in springs of hot water which continue for centuries to maintain their

[1] *Allgemeine Geologie als exacte Wissenschaft*, p. 42.

[2] The late David Forbes suggested that the planet might be supposed to consist of three layers of uniform densities, enclosed one within the other, the density increasing towards the centre in arithmetical progression. Allowing 2·5 as the specific gravity of the crust or outer layer, he assigned 12·0 or thereabouts as that of the middle layer, and supposed that the inner nucleus might possess one averaging 20·0. (*Popular Science Review*, April, 1869.) Materials do not yet exist for any satisfactory conclusions on this subject.

heat. Thermal springs, however, are not confined to volcanic districts. They sometimes rise even in regions many hundreds of miles distant from any active volcanic vent. The hot springs of Bath (temp. 120° Fahr.) and Buxton (temp. 82° Fahr.) in England are fully 900 miles from the Icelandic volcanoes on the one side and 1100 miles from those of Italy and Sicily on the other.

(3.) *Borings, Wells, and Mines.*—The influence of the seasonal changes of temperature extends downward from the surface to a depth which varies according to latitude, to the thermal conductivity of the soils and rocks, and perhaps to other causes. The cold of winter and the heat of summer may be regarded as following each other in successive waves downward, until they disappear along a limit at which the temperature remains constant. This zone of invariable temperature is commonly believed to lie at a depth of somewhere between 60 and 80 feet in temperate regions. At Yakutsk in Eastern Siberia (lat. 62° N.), however, the soil is permanently frozen to a depth of about 700 feet.[1] In Java, on the other hand, a constant temperature is said to be met with at a depth of only 2 or 3 feet.[2]

It is a remarkable fact, now verified by observation all over the world, that below the limit of the influence of ordinary seasonal changes the temperature, so far as we yet know, is nowhere found to diminish downwards. It always rises; and its rate of increment never falls much below the average. The only exceptional cases occur under circumstances not difficult of explanation. On the one hand, the neighbourhood of hot-springs, of large masses of lava, or of other manifestations of volcanic activity, may raise the subterranean temperature much above its normal condition; and this augmentation may not disappear for many thousand years after the volcanic activity has wholly ceased, since the cooling down of a subterranean mass of lava would necessarily be a very slow process. It has even been proposed to estimate the age of subterranean masses of intrusive lava from their excess of temperature above the normal amount for their isogeotherms (lines of equal earth-temperature), some probable initial temperature and rate of cooling being assumed. On the other hand, the spread of a thick mass of snow and ice over any considerable area of the earth's surface, and its continuance there for several thousand years, would so depress the isogeotherms that for many centuries afterwards there would be a fall of temperature for a certain distance downwards. At the present day, in at least the more northerly parts of the northern hemisphere, there are such evidences of a former more rigorous climate, as in the well sinking at Yakutsk just referred to.[3] Sir William Thomson[4]

[1] Helmersen, *Brit. Assoc. Report*, 1871. [2] Junghuhn's *Java*, ii. p. 771.

[3] Professor Prestwich (*Inaugural Lecture*, 1875, p. 45) has suggested that to the more rapid refrigeration of the earth's surface during this cold period, and to the consequent depression of the subterraneous isothermal lines, the alleged present comparative quietude of the volcanic forces is to be attributed, the internal heat not having yet recovered its dominion in the outer crust.

[4] *Brit. Assoc. Reports*, 1876, Sections, p. 3.

has calculated that any considerable area of the earth's surface covered for several thousand years by snow or ice, and retaining, after the disappearance of that frozen covering, an average surface temperature of 13° C., "would during 900 years show a decreasing temperature for some depth down from the surface, and 3600 years after the clearing away of the ice would still show residual effect of the ancient cold, in a half rate of augmentation of temperature downwards in the upper strata, gradually increasing to the whole normal rate, which would be sensibly reached at a depth of 600 metres." But beneath the limit to which the influence of the changes of the seasons extends, observations in most parts of the globe show that the temperature invariably rises as we penetrate towards the interior of the earth. According to present knowledge, the average rate of increase amounts to 1° Fahr. for every 50 or 60 feet of descent, and this rise is found whether the boring be made at the sea-level or on elevated ground. The subjoined table gives the results of temperature observations at widely separated localities:[1]—

		Feet.
Dukinfield, near Manchester (2040 ft., Coal measures)	1° Fahr., for every	83·2
Rose Bridge, Wigan (2445 ft., Coal measures) . .	" "	54·3
South Balgray, Glasgow (525 ft., Coal measures) .	" "	41
Kentish Town, London (1100 ft., London clay, Chalk, Gault, &c.)	" "	54·6
La Chapelle, Paris (660 metres, Chalk, &c.) . . .	" "	84
Grenelle Well, Paris (1795·6 ft. do.)	" "	56·9
St. André, do. (263 metres, do.)	" "	56·4
Neu Salzwerk boring, Westphalia (2281 ft.) . . .	" "	54·68
Mendorff bore, near Luxembourg (2394 ft.) . . .	" "	57·0
Bore near Geneva	" "	55
Mont Cenis tunnel (5280 ft. below summit of Mount Frejus, metamorphic rocks)	" " (?)	81
Yakutsk, Siberia (656 ft., limestone, &c. and granite).	" "	60

Irregularities in the Downward Increment of Heat.—While these examples prove a progressive increase of temperature, they show also that this rate of increase is not strictly uniform. The more detailed observations which have been made in recent years have brought to light the important fact that considerable variations in the rate of increase take place even in the same bore. If, for instance, we examine the temperatures obtained at different depths in the Rose Bridge colliery shaft cited in the foregoing list, we find them to read as in the following columns:—

Depth in Yards.	Temperature (Fahr.).	Depth in Yards.	Temperature (Fahr.).
558	78	745	89
605	80	761	90½
630	83	775	91½
663	85	783	92
671	86	800	93
679	87	806	93½
734	88½	815	94

[1] See "Reports of Committee on Underground Temperature," *Brit. Assoc. Rep.* from 1868 to 1879.

At La Chapelle, in an important well made for the water-supply of Paris, observations have been taken of the temperature at different depths, as shown in the subjoined table:—[1]

Depth in Metres.	Temperature (Fahr.).	Depth in Metres.	Temperature (Fahr.).
100	59·5	500	72·6
200	61·8	600	75·0
300	65·5	660	76·0
400	69·0		

In drawing attention to the temperature-observations at the Rose Bridge colliery—the deepest mine in Great Britain—Professor Everett points out that, assuming the surface temperature to be 49° Fahr., in the first 558 yards the rate of rise of temperature is 1° for 57·7 feet; in the next 257 yards it is 1° in 48·2 feet; in the portion between 605 and 671 yards—a distance of only 198 feet—it is 1° in 33 feet; in the lowest portion of 432 feet it is 1° in 54 feet.[2] When such irregularities occur in the same vertical shaft, it is not surprising that the average should vary so much in different places.

There can be little doubt that one main cause of these variations is to be sought in the different thermal conductivities of the rocks of the earth's crust. The first accurate measurements of the conducting powers of rocks were made by the late Professor J. D. Forbes at Edinburgh (1837–1845). He selected three sites for his thermometers, one in "trap-rock" (a porphyrite of Lower Carboniferous age), one in loose sand, and one in sandstone, each set of instruments being sunk to depths of 3, 6, 12 and 24 French feet from the surface. He found that the wave of summer heat reached the bulb of the deepest instrument (24 feet) on 4th January in the trap-rock, on 25th December in the sand, and on 3rd November in the sandstone, the trap-rock being the worst conductor and the solid sandstone by far the best.[3]

The British Association has recently appointed a committee to investigate this subject in greater detail. Already some important determinations have been made by it regarding the absolute conductivities of various rocks. As a rule, the lighter and more porous rocks offer the greatest resistance to the passage of heat, while the more dense and crystalline offer the least resistance. The resistance of opaque white quartz is expressed by the number 114, that of basalt by 273, while that of cannel coal stands very much higher at 1538, or more than thirteen times that of quartz.[4]

It is evident also that, from the texture and structure of most rocks, the conductivity must vary in different directions through the

[1] "Report of Committee on Underground Temperature," *Brit. Assoc. Rep.*, 1873, p. 254.

[2] "Report of Committee on Underground Temperature," *Brit. Assoc. Rep.* for 1870, p. 31.

[3] *Trans. Roy. Soc. Edin.*, xvi. p. 211.

[4] Herschel and Lebour, *Brit. Assoc. Rep.*, 1875, p. 59.

same mass, heat being more easily conducted along than across the "grain," the bedding, and the other numerous divisional surfaces. Experiments have been made to determine these variations in a number of rocks. Thus, the conductivity in a direction transverse to the divisional planes being taken as unity, the conductivity parallel with these planes was found in a variety of magnesian schist to be 4·028. In certain slates and schistose rocks from central France the ratio varied from 1 : 2·56 to 1 : 3·952. Hence in such fissile rocks as slate and mica-schist, heat may travel four times more easily along the planes of cleavage or foliation than across them.[1]

In reasoning upon the discrepancies in the rate of increase of subterranean temperatures, we must also bear in mind that certain kinds of rock are more liable than others to be charged with water, and that, in almost every boring or shaft, one or more horizons of such water-bearing rocks are met with. The effect of this interstitial water is to diminish thermal resistance. Dry red brick has its resistance lowered from 680 to 405 by being thoroughly soaked in water, its conductivity being thus increased 68 per cent. A piece of sandstone has its conductivity heightened to the extent of 8 per cent. by being wetted.[2]

Mr. Mallet has contended that the variations in the amount of increase in subterranean temperature are too great to permit us to believe them to be due merely to differences in the transmission of the general internal heat, and that they point to local accessions of heat arising from transformation of the mechanical work of compression, which is due to the constant cooling and contraction of the globe.[3] But it may be replied that these variations are not greater than, from the known divergences in the conductivities of rocks, they might fairly be expected to be.

Probable Condition of the Earth's Interior.—Various theories have been propounded on this subject. There are only three which merit serious consideration. (1.) One of these supposes the planet to consist of a solid crust and a molten interior. (2.) The second holds that, with the exception of local vesicular spaces, the globe is solid and rigid to the centre. (3.) The third contends that while the mass of the globe is solid, there lies a liquid substratum beneath the crust.

1. *The arguments in favour of internal liquidity* may be summed up as follows. (*a*.) The ascertained rise of temperature inwards from the surface is such that, at a very moderate depth, the ordinary melting point of even the most refractory substances would be reached. At 20 miles the temperature, if it increases progressively, as it does in the depths accessible to observation, must be about

[1] "Report of Committee on Thermal Conductivities of Rock," *Brit. Assoc. Rep.* 1875, p. 61. Jannettaz, *Bull. Soc. Géol. France* (April–June, 1874), ii. p. 264. This observer has carried out a series of detailed researches on the propagation of heat through rocks, which will be found in *Bull. Soc. Géol. France*, tomes i.—vi. (3rd series).

[2] Herschel and Lebour, *Brit. Assoc. Rep.* 1875, p. 58.

[3] "Volcanic Energy," *Phil. Trans.* 1875.

1760° Fahr.; at 50 miles it must be 4600°, or far higher than the fusing-point even of so stubborn a metal as platinum, which melts at 3080° Fahr.[1] (*b.*) All over the world volcanoes exist from which steam and torrents of molten lava are from time to time erupted. Abundant as are the active volcanic vents, they form but a small proportion of the whole which have been in operation since early geological time. It has been inferred therefore that these numerous funnels of communication with the heated interior could not have existed and poured forth such a vast amount of molten rock, unless they drew their supplies from an immense internal molten nucleus. (*c.*) When the products of volcanic action from different and widely-separated regions are compared and analysed, they are found to exhibit a remarkable uniformity of character. Lavas from Vesuvius, from Hecla, from the Andes, from Japan, and from New Zealand present such an agreement in essential particulars as, it is contended, can only be accounted for on the supposition that they have all emanated from one vast common source.[2] (*d.*) The abundant earthquake shocks which affect large areas of the globe are maintained to be inexplicable unless on the supposition of the existence of a thin and somewhat flexible crust. These arguments, it will be observed, are only of the nature of inferences drawn from observations of the present constitution of the globe. They are based on geological data, and have been frequently urged by geologists as supporting the only view of the nature of the earth's interior compatible with geological evidence.

2. *The arguments against the internal fluidity of the earth* are based on physical and astronomical considerations of the greatest importance. They may be arranged as follows:—

(*a.*) Argument from precession and nutation.—The problem of the internal condition of the globe was attacked as far back as the year 1839 by Hopkins, who endeavoured to calculate how far the planetary motions of precession and nutation would be influenced by the solidity or liquidity of the earth's interior. He found that the precessional and nutational movements could not possibly be as they are if the planet consisted of a central core of molten rock surrounded with a crust of twenty or thirty miles in thickness, that the least possible thickness of crust consistent with the existing movements was from 800 to 1000 miles, and that the whole might even be solid to the centre, with the exception of comparatively small vesicular spaces filled with melted rock.[3]

M. Delaunay,[4] threw doubt on Hopkins's views, and suggested

[1] But Sir W. Thomson has shown that while the rate of increase of temperature is probably 1° for every 51 feet for the first 100,000 feet, it will begin to diminish below that limit, being only 1° in 2550 feet at 800,000 feet, and then rapidly lessening. *Trans. Roy. Soc. Edin.* xxiii., p. 163.

[2] See D. Forbes, *Popular Science Review*, April 1869.

[3] *Phil. Trans.* 1839, p. 381; 1840, p. 193; 1842, p. 43; *Brit. Assoc.* 1847.

[4] In a paper on the hypothesis of the interior fluidity of the globe, *Comptes-rendus*, July 13, 1868. *Geol. Mag.* v. p. 507. See also a paper by H. Hennessy, *Comptes-rendus* 6 March, 1871, and *Geol. Mag.* viii. p. 216.

that, if the interior were a mass of sufficient viscosity, it might behave as if it were a solid, and thus the phenomenon of precession and nutation might not be affected. Sir William Thomson, who had already arrived at the conclusion that the interior of the globe must be solid, and acquiesced generally in Hopkins's conclusions, pointed out that M. Delaunay had not worked out the problem mathematically, otherwise he could not have failed to see that the hypothesis of a viscous and quasi-rigid interior "breaks down when tested by a simple calculation of the amount of tangential force required to give to any globular portion of the interior mass the precessional and nutational motions which, with other physical astronomers, he attributes to the earth as a whole."[1] Sir William, in making this calculation, holds that it demonstrates the earth's crust down to depths of hundreds of kilometres to be capable of resisting such a tangential stress (amounting to nearly $\frac{1}{10}$th of a gramme weight per square centimetre) as would with great rapidity draw out of shape any plastic substance which could properly be termed a viscous fluid. "An angular distortion of 8″ is produced in a cube of glass by a distorting stress of about ten grammes weight per square centimetre. We may therefore safely conclude that the rigidity of the earth's interior substance could not be less than a millionth of the rigidity of glass without very sensibly augmenting the lunar nineteen-yearly nutation."[2]

In Hopkins's hypothesis he assumed the crust to be infinitely rigid and unyielding, which is not true of any material substance. Sir William Thomson has recently returned to the problem, in the light of his own researches in vortex-motion. He now finds that, while the argument against a thin crust and vast liquid interior is still invincible, the phenomena of precession and nutation do not decisively settle the question of internal fluidity, though the solar semi-annual and lunar fortnightly nutations absolutely disprove the existence of a thin rigid shell full of liquid. If the inner surface of the crust or shell were rigorously spherical, the interior mass of supposed liquid could experience no precessional or nutational influence, except in so far as, if heterogeneous in composition, it might suffer from external attraction due to non-sphericity of its surfaces of equal density. But "a very slight deviation of the inner surface of the shell from perfect sphericity would suffice, in virtue of the quasi-rigidity due to vortex-motion, to hold back the shell from taking sensibly more precession than it would give to the liquid, and to cause the liquid (homogeneous or heterogeneous) and the shell to have sensibly the same precessional motion as if the whole constituted one rigid body."[3]

The assumption of a comparatively thin crust requires that the crust shall have such perfect rigidity as is possessed by no known substance. The tide-producing force of the moon and sun exerts

[1] *Nature*, February 1, 1872. [2] *Loc. cit.* p. 258.
[3] Sir W. Thomson, *Brit. Assoc. Rep.* 1876, Sections, p. 5.

such a strain upon the substance of the globe, that it seems in the highest degree improbable that the planet could maintain its shape as it does unless the supposed crust were at least 2000 or 2500 miles in thickness.[1] That the solid mass of the earth must yield to this strain is certain, though the amount of deformation is so slight as to have hitherto escaped all attempts to detect it.[2] Had the rigidity been even that of glass or of steel, the deformation would probably have been by this time detected, and the actual phenomena of precession and nutation, as well as of the tides, would then have been very sensibly diminished.[3] The conclusion is thus reached that the mass of the earth "is on the whole more rigid certainly than a continuous solid globe of glass of the same diameter."[4]

(*b.*) Argument from the tides.—The phenomena of the oceanic tides are only explicable on the theory that the earth is either solid to the centre, or possesses so thick a crust (2500 miles or more) as to give to the planet practical solidity. Sir William Thomson remarks that "were the crust of continuous steel, and 500 kilometres thick, it would yield very nearly as much as if it were india-rubber to the deforming influences of centrifugal force, and of the sun's and moon's attractions." It would yield, indeed, so freely to these attractions "that it would simply carry the waters of the ocean up and down with it, and there would be no sensible tidal rise and fall of water relatively to land."[5] Mr. George H. Darwin in the series of papers already referred to, has investigated mathematically the bodily tides of viscous and semi-elastic spheroids, and the character of the ocean tides on a yielding nucleus.[6] His results tend to increase the force of Sir William Thomson's argument, since they show that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition," the effective rigidity of the whole globe being very great.

(*c.*) Argument from relative densities of melted and solid rock.—The two preceding arguments must be considered decisive against the hypothesis of a thin shell or crust covering a nucleus of molten matter. It has been further urged, as an objection to this hypothesis, that cold solid rock is necessarily more dense than hot melted rock, and that even if a thin crust were formed over the central molten globe it would immediately break up and the fragments would sink towards the centre.[7] Undoubtedly this would happen were the material of the earth's mass of the same density throughout. But, as has been already pointed out, the specific gravity of the interior is at least twice as much as that of the visible parts of the crust. If this difference be due, not merely to the effect of pressure, but to the

[1] Thomson, *Proc. Roy. Soc.* April, 1862.
[2] See *Association Française pour l'Avancement des Sciences*, v. p. 281.
[3] Thomson, *loc. cit.*
[4] Thomson, *Trans. Roy. Soc. Edin.* xxiii. p. 157.
[5] Thomson, *Brit. Assoc. Rep.* 1876, Sections, p. 7.
[6] *Phil. Trans.* 1879, Part I.
[7] This objection has been repeatedly urged by Sir William Thomson. See *Trans. Roy. Soc. Edin.* xxiii. p. 157; and *Brit. Assoc. Rep.* 1876, Sections, p. 7.

presence in the interior of intensely heated metallic substances, we cannot suppose that solidified portions of such rocks as granite and the various lavas could ever have sunk into the centre of the earth, so as to build up there the honey-combed cavernous mass which might have served as a nucleus in the ultimate solidification of the whole planet; though the earliest formed portions of the comparatively light crust would no doubt descend until they reached a stratum with specific gravity agreeing with their own, or until they were again melted.[1]

3. *Hypothesis of a liquid substratum between a solid nucleus and the crust.*—Since the early and natural belief in the liquidity of the earth's interior has been so weightily opposed by physical arguments, geologists have endeavoured to modify it in such a way as, if possible, to satisfy the requirements of physics, while at the same time providing an adequate explanation of the corrugation of the earth's crust, the phenomena of volcanoes, &c.[2] Professors Shaler[3] and Le Conte,[4] and Mr. Fisher[5] have advocated the existence of a fluid or viscous substratum beneath the crust, the contraction and consolidation of which produced the corrugations of the rocks and of the surface. "The increase of temperature," says Mr. Fisher, "though rapid near the surface, becomes less and less as we descend, so that, if the earth were once wholly melted, the temperature near the centre is not very greatly above what it is at a depth which, compared to the earth's radius, is small. Consequently, if it requires great pressure to solidify the materials at such a temperature, it is probable that the melting temperature may be reached before the pressure is sufficient to solidify." The crust, of course, must be able to sustain itself on the corrugated surface of the supposed viscous layer without breaking up and sinking. The same writer has suggested that the observed amount of corrugation is more than can be accounted for even on this hypothesis, and that the shrinkage may have been due not merely to cooling, but to the escape of water from the interior in the form of the super-heated steam of volcanic vents.[6] More recently Herr Siemens has been led, from observations made in May 1878 at Vesuvius, to conclude that vast quantities of hydrogen gas, or combustible compounds of hydrogen, exist in the earth's interior, and that these, rising and exploding in the funnels of volcanoes, give rise to the detonations and clouds of steam.[7]

It must be admitted that the wide-spread proofs of great crumpling of the rocks of the crust present a serious difficulty, for

[1] See D. Forbes, *Geol. Mag.* vol. iv. p. 435.
[2] See Dana in *Silliman's Journal*, iii. (1847) p. 147. *Amer. Journ. Science* (1873).
[3] *Proc. Bost. Nat. Hist. Soc.* xi. (1868) p. 8. *Geol. Mag.* v. p. 511.
[4] *Amer. Journ. Sci.* 1872, 1873.
[5] *Geol. Mag.* v. (new series) pp. 291 and 551. See also Hill, *op. cit.* pp. 262, 479. The idea of a viscous layer between the solidifying central mass and the crust was present in Hopkins' mind. *Brit. Assoc.* 1848. Reports, p. 48.
[6] *Phil. Mag.* Oct. 1875.
[7] *Monatsbericht der K. preuss. Akad. Wissenschaft*, 1878, p. 558. See also Book iii. Part i. for an account of Fouqué's observations on the discharge of hydrogen at Santorin.

they indicate a capability of yielding to strain such as might be supposed hardly possible in a globe possessing on the whole the rigidity of steel or glass. Still we ought to remember how small a part of the whole terrestrial area is occupied by those portions of land from the investigation of which all our direct evidence as to the nature of the earth's crust has been obtained. From the earliest times the existing continental regions seem to have specially suffered from the efforts of the planet to adjust its external form to its diminishing diameter, and its lessening rapidity of rotation. They have served as lines of relief from the strain of compression during many successive epochs. It is along their axial lines,—their long dominant mountain ranges, that we should naturally look for evidence of corrugation. Away from these lines of weakness the ground has been upraised for thousands of square miles without plication of the rocks, as in the instructive region of the Western Territories of North America. Nor is there any sign that corrugation takes place beneath the great oceanic areas of subsidence.

It appears highly probable that the substance of the earth's interior is at the melting point proper for the pressure at each depth. Any relief from pressure therefore may allow of the liquefaction of the matter so relieved. Such relief is doubtless afforded by the corrugation of mountain chains and other terrestrial ridges. And it is in these lines of uprise that volcanoes and other manifestations of subterranean heat actually show themselves.

§ 4. **Age of the Earth and Measures of Geological Time.**—The age of our planet is a problem which may be attacked either from the geological or physical side.

1. The geological argument rests chiefly upon the observed rates at which geological changes are being effected at the present time, and is open to the obvious preliminary objection that it assumes the existing rate of change as the measure of past revolutions,—an assumption which may be entirely erroneous, for the present may be a period when all geological events march forward more slowly than they used to do. The argument proceeds on data partly of a physical and partly of an organic kind. (*a.*) The physical evidence is derived from such facts as the observed rates at which the surface of a country is lowered by rain and streams, and new sedimentary deposits are formed. These facts will be more particularly dwelt upon in later sections of this volume. If we assume that the land has been worn away, and that stratified deposits have been laid down nearly at the same rate as at present, then we must admit that the stratified portion of the crust of the earth must represent a very vast period of time.[1] (*b.*) On the other hand, human experience, so

[1] Dr. Croll puts this period at not less, but possibly much more, than 60 million years. Dr. Haughton gives a much more extended period. Estimating the present rate of deposit of strata at 1 foot in 8616 years, assuming the former rate to have been ten times more rapid, or 1 foot in 861·6 years, and taking the thickness of the stratified rocks of the earth's crust at 177,200 feet, he obtains a minimum of 200,000,000 years for the whole duration of geological time: *Six Lectures on Physical Geography*, 1880, p. 94.

far as it goes, warrants the belief that changes in the organic world proceed with extreme slowness. Yet in the stratified rocks of the terrestrial crust we have abundant proof that the whole fauna and flora of the earth's surface have passed through numerous cycles of revolution,—species, genera, families, orders, appearing and disappearing many times in succession. On any supposition it must be admitted that these vicissitudes in the organic world can only have been effected with the lapse of vast periods of time, though no reliable standard seems to be available whereby these periods are to be measured. The argument from geological evidence is strongly in favour of an interval of probably not much less than 100 million years since the earliest forms of life appeared upon the earth, and the oldest stratified rocks began to be laid down.

2. The argument from physics as to the age of our planet is based by Sir William Thomson upon three kinds of evidence:—(1) the internal heat and rate of cooling of the earth; (2) the tidal retardation of the earth's rotation; and (3) the origin and age of the sun's heat.

(1.) Applying Fourier's theory of thermal conductivity, he pointed out some years ago (1862) that in the known rate of increase of temperature downward beneath the surface, and the rate of loss of heat from the earth, we have a limit to the antiquity of the planet. He showed, from the data available at the time, that the superficial consolidation of the globe could not have occurred less than 20 million years ago, or the underground heat would have been greater than it is; nor more than 400 million years ago, otherwise the underground temperature would have shown no sensible increase downwards. He admitted that very wide limits were necessary. In more recently discussing the subject, he inclines rather towards the lower than the higher antiquity, but concludes that the limit, from a consideration of all the evidence, must be placed within some such period of past time as 100 millions of years.[1]

(2.) The reasoning from tidal retardation proceeds on the admitted fact that, owing to the friction of the tide-wave, the rotation of the earth is retarded, and is therefore slower now than it must have been at one time. Sir William Thomson contends that had the globe become solid some 10,000 million years ago, or indeed any high antiquity beyond 100 million years, the centrifugal force due to the more rapid rotation must have given the planet a very much greater polar flattening than it actually possesses. He admits, however, that though 100 million years ago that force must have been about 3 per cent. greater than now, yet "nothing we know regarding the figure of the earth and the disposition of land and water would justify us in saying that a body consolidated when there was more centrifugal force by 3 per cent. than now might

[1] *Trans. Roy. Soc. Edin.* xxiii. p. 157. *Trans. Geol. Soc. Glasgow*, iii. p. 25. Professor Tait reduces the period to 10 or 15 millions. *Recent Advances in Physical Science*, p. 167.

not now be in all respects like the earth, so far as we know it at present."[1]

(3.) The third kind of evidence leads to results confessedly less emphatic than those from the two previous lines of reasoning. It is based upon calculations as to the amount of heat that would be available by the falling together of the masses from space, which gave rise by their impact to our sun, and the rate at which this heat has been radiated. Assuming that the sun has been cooling even at a uniform rate, Professor Tait comes to the conclusion that it cannot have supplied the earth, even at the present rate, for more than about 15 or 20 million years.[2]

Part II.—An Account of the Composition of the Earth's Crust—Minerals and Rocks.

The earth's crust is composed of mineral matter in various aggregates included under the general term Rock. A rock may be defined as a mass of matter composed of one or more simple minerals, having usually a variable chemical composition with no necessarily symmetrical external form, and ranging in cohesion from mere loose débris up to the most compact stone. Granite, lava, sandstone, limestone, gravel, sand, mud, soil, marl and peat, are all recognized in a geological sense as rocks.

It will be most convenient to treat—1st, of the general chemical constitution of the crust; 2nd, of the minerals of which rocks mainly consist; 3rd, of the external characters, and, 4th, of the internal texture and structure, of rocks; 5th, of the classification of rocks; 6th, of the more important rocks occurring as constituents of the earth's crust; and 7th, of the methods employed for their determination.

§ i. *General Chemical Constitution of the Crust.*

Direct acquaintance with the chemical constitution of the globe must obviously be limited to that of the crust, though by inference we may eventually reach highly probable conclusions regarding the constitution of the interior. Chemical research has discovered that sixty-four[3] simple or as yet undecomposable bodies, called elements, in various proportions and compounds, constitute the accessible part of the crust. Of these, however, the great majority are comparatively of rare occurrence. The crust, so far as we can examine it, is mainly

[1] *Trans. Geol. Soc. Glasgow*, iii. p. 16. Professor Tait, in repeating this argument, concludes that, taken in connection with the previous one, "it probably reduces the possible period which can be allowed to geologists to something less than 10 millions of years." *Op. cit.* p. 174.

[2] *Op. cit.* p. 174.

[3] This number has within the last two years been increased by the alleged discovery of no fewer than fourteen new metals. Some of these bodies, however, have not yet been satisfactorily proved to be new. T. S. Humpidge, *Nature* xxii. p. 232.

built up of about sixteen elements, which may be arranged in the two following groups, the most abundant bodies being placed first in each list:—

Metalloids.	Atomic Weight.	*Metals.*	Atomic Weight.
Oxygen	15·96	Aluminium	27·30
Silicon	28·00	Calcium	39·90
Carbon	11·97	Magnesium	23·94
Sulphur	31·98	Potassium	39·04
Hydrogen	1·00	Sodium	22·99
Chlorine	35·37	Iron	55·90
Phosphorus	30·96	Manganese	54·80
Fluorine	19·10	Barium	136·80

The sixteen elements here mentioned form about ninety-nine parts of the earth's crust; the other elements constitute only about a hundreth part, though they include gold, silver, copper, tin, lead, and the other useful metals, iron excepted. By far the most abundant and important element is Oxygen. It forms about 23 per cent. by weight of air, 88·87 per cent. of water, and about a half of all the rocks which compose the visible portion or crust of the globe. Another metalloid, Silicon, always united with oxygen, ranks next in abundance as a constituent of the crust. Of the remaining metalloids, Carbon and Sulphur sometimes occur in the free state, but usually in combination with oxygen or some metal. Chlorine (save perhaps at volcanic vents) does not occur in a free state, but is abundant in combination with the alkalies, especially with sodium. Fluorine is always found in combination, and has never yet been isolated by artificial chemical processes. It is the only element which has not been combined with oxygen. It chiefly occurs in union with Calcium as the mineral fluor-spar; but traces of its presence have been detected in other minerals, in sea-water, and in the bones, teeth, blood and milk of mammalia. Hydrogen occurs chiefly in combination with oxygen as the oxide, water, of which it forms 11·13 per cent. by weight; also in combination with carbon as the hydrocarbons (mineral oils and gases), produced by the slow decomposition of organic matter. Phosphorus occurs with oxygen principally in calcic phosphate. Of the metals, a few are found in the native state (gold, silver, copper, &c.), but those of importance in the framework of the earth's crust have entered into combination with metalloids or with each other.

So far as accessible to observation, the outer portion of our planet consists mainly of metalloids. Its metallic constituents have already in great part entered into combination with oxygen, so that the atmosphere contains the residue of that gas which has not yet united itself to terrestrial compounds. In a broad view of the arrangement of the chemical elements in the external crust, the suggestive speculation of Durocher deserves attention.[1] He regarded all rocks as referable to two layers or magmas co-existing in the earth's crust

[1] *Ann. des Mines*, 1857. Translated by Haughton, *Manual of Geology*, 1866, p. 16.

the one beneath the other, according to their specific gravities. The upper or outer layer, which he termed the acid or siliceous magma, contains an excess of silica, and has a mean density of 2·65. The lower or inner layer, which he called the basic magma, has from six to eight times more of the earthy bases and iron oxides, with a mean density of 2·96. To the former he assigned the early plutonic rocks, granite, felsite, &c., with the more recent trachytes; to the latter he relegated all the heavy lavas, basalts, diorites, &c. The ratio of silica is 7 in the acid magma to 5 in the basic. Though the proportion of this acid or of the earthy and metallic bases cannot be regarded as any certain evidence of the geological date of rocks, nor of their probable depth of origin, it is nevertheless a fact that (with many important exceptions) the eruptive rocks of the older geological periods are very generally super-silicated and of lower specific gravity, while those of later time are very frequently poor in silica, but rich in the earthy bases and in iron and manganese, with a consequent higher specific gravity. The latter, according to Durocher, have been forced up from a lower zone through the lighter siliceous crust. The sequence of volcanic rocks as first announced by Richthofen, has an interesting connection with this speculation.

The main mass of the earth's crust is composed of a few predominant compounds. Of these in every respect the most abundant and important is Silicon dioxide or Silica (Kieselerde) $Si\ O_2$. It forms more than one half of the known crust, seeing that it enters as a main ingredient into the composition of most crystalline and fragmental rocks. It occurs in the free state as the abundant rock-forming mineral quartz. Being one of the acid-forming oxides (H_4SiO_4, Silicic acid, Kieselsäure) it forms combinations with alkaline, earthy, and metallic bases which appear as the prolific and universally diffused family of the silicates. Moreover it is present in solution in terrestrial and oceanic waters, from which it is deposited in pores and fissures of rocks. It is likewise secreted from these waters by abundantly diffused species of plants and animals (diatoms, radiolarians, &c.) It has been largely effective in replacing the organic textures of former organisms, and thus preserving them as fossils.

Alumina or Aluminium oxide (Thonerde), Al_2O_3, occurs sparingly native as Corundum, which, however, according to F. A. Genth, was the original condition of many now abundant complex aluminous minerals and rocks. The most common condition of aluminium is in union with silica. In this form it constitutes the basis of the vast family of the aluminous silicates, of which so large a portion of the crystalline and fragmental rocks consists. Exposed to the atmosphere, these silicates lose some of their more soluble ingredients, and the remainder forms an earth or clay consisting chiefly of silicate of aluminium.

Carbon in the various kinds of coal takes rank as an important rock-forming element. But its most universal condition is in carbon

dioxide, CO_2 present in the air, in rain, in the sea, and in ordinary terrestrial waters. This oxide is soluble in water,[1] giving rise then to a dibasic acid termed Carbonic Acid (Kohlensäure) $CO(OH)_2$ or H_2CO_3, which, in combination with calcium, has been instrumental in the formation of vast masses of solid rock. Carbon dioxide constitutes a fifth part of the weight of ordinary limestone.

Sulphur (Soufre, Schwefel) S, occurs uncombined in occasional deposits like those of Sicily and Naples, to be afterwards described, also in union with iron and other metals as sulphides; but its principal condition as a rock-builder is in combination with oxygen as sulphuric acid (Schwefelsäure) H_2SO_4 which with lime forms beds of sulphate.

Calcium enters into the composition of many crystalline rocks in combination with silica and with other silicates. But its most abundant form is in union with carbon dioxide when it appears as the mineral calcite ($CaCO_3$) or the rock limestone. Calcium carbonate, being soluble in water containing carbonic acid, is one of the most universally diffused mineral ingredients of natural waters. It supplies the varied tribes of mollusca, corals, and many other invertebrates with the mineral substance for the secretion of their tests and skeletons. Such too has been its office from remote geological periods, as is shown by the vast masses of organically formed limestone which enter so conspicuously into the structure of the continents. In combination with sulphuric acid, calcium forms important beds of gypsum and anhydrite.

Magnesium, Potassium, and Sodium play a less conspicuous but still essential part in the composition of the earth's crust. Magnesium in combination with silica forms a class of silicates of prime importance in the composition of volcanic and metamorphic rocks. As a carbonate it unites with calcium carbonate to form the widely diffused rock, dolomite. Potassium or Sodium combined with silica is present in small quantity in most silicates. In union with chlorine as common salt sodium is the most important mineral ingredient of sea-water, and can be detected in minute quantities in air, rain, and in terrestrial waters. In the old chemical formulæ hitherto employed in mineralogy the metals of the alkalies and alkaline earths are represented as oxides. Thus lime (calcium monoxide), soda (sodium monoxide), potash (potassium monoxide), magnesia (magnesium oxide), are denoted as in union with carbonic acid, sulphuric acid, silica, &c., forming carbonates, sulphates, silicates of lime, soda, &c.

Iron and Manganese are the two most common heavy metals, occurring both in the form of ores and as constituents of rocks. Iron is the great pigment of nature. Its peroxide, sesquioxide, or ferric oxide forms large mineral masses, and together with the protoxide or ferrous oxide occurs in smaller or larger proportions in

[1] One volume of water at 0° C. dissolves 1·7967 volumes of carbon dioxide; at 15° C. the amount is reduced to 1·0020 volumes.

the great majority of crystalline rocks. Iron is removed in solution in the water of springs and precipitated as a hydrous peroxide. Manganese is commonly associated with iron in minute proportions in igneous rocks, and being similarly removed in solution in water, is thrown down as bog manganese or wad.

Silicic Acid, Carbonic Acid, and Sulphuric Acid are the three acids with which most of the bases that compose the earth's crust have been combined. With these we may connect the water which, besides merely percolating through rocks, or existing as water of crystallization in minerals, has been chemically absorbed in the process of hydration, and which thus constitutes more than 10 or even 20 per cent. of some rocks (gypsum).

Although every mineral may be made to yield data of more or less geological significance, it will be needful to bring under the notice of the student here only those minerals which enter as chief ingredients into the composition of rock-masses, or which are of frequent occurrence as accessories. Of the species thus introduced, it will be proper to dwell more particularly on those of their characters which are of chief interest from a geological point of view, such as their modes of occurrence in relation to the genesis of rocks, and their weathering as indicative of the nature of rock-decomposition. It will thus be unavoidable that subjects must be referred to by anticipation which will find fuller treatment in the sequel. But the cross references will, it is hoped, enable the reader to pass with ease from the enumeration of the facts, which is what is chiefly intended in the present section, to the discussion of the meaning of these facts as given in subsequent pages.

§ ii. *Rock-forming Minerals.*

Minerals as constituents of rocks occur in four conditions, according to the circumstances under which they have been produced.

1. *Crystalline*, as (*a*) more or less regularly defined crystals; (*b*) amorphous granules or aggregations having an internal crystalline structure in most cases easily recognizable with polarized light; (*c*) "crystallites" or "microliths," incipient forms of crystallization, which are described on p. 100. The crystalline condition may arise either from igneous fusion or from aqueous solution.[1]

2. *Glassy* or *vitreous*, as a natural glass usually including either crystals or crystallites, or both. Minerals have assumed this condition from a state of fusion. The glass may consist of several minerals fused into one homogeneous substance. Where it has been "devitrified," that is, has assumed a lithoid or stony structure, these component minerals crystallize out of the glassy magma, and may be recognised in various stages of growth.

3. *Colloid*, as a jelly-like though stony substance, of which

[1] For the microscopic characters of minerals and rocks, see p. 94.

calcedony may be taken as the type. Minerals in this form have probably always resulted as a deposition from aqueous solutions.

4. *Amorphous*, having no crystalline structure or form, and occurring in indefinite masses, granules, streaks, tufts, stainings, or other irregular modes of occurrence.

A mineral which has replaced another and has assumed the external form of the mineral so replaced, is termed a *Pseudomorph*. A mineral which encloses another has been called a *Perimorph;* one enclosed within another, an *Endomorph*.

Minerals may either be essential or accessory, original or secondary constituents of rocks. A mineral is an essential ingredient when its absence would so alter the character of a rock as to make it something fundamentally different. The quartz of granite, for example, is an essential constituent of that rock, the removal of which would make some other petrographical species. All essential minerals are original constituents of a rock, but all the original constituents are not essential. In granite, for example, topaz, beryl, sphene, and other minerals often occur under circumstances which show that they crystallized out of the original magma of the rock. But they form so trifling a proportion in the total mass, and their absence would so little affect the general character of that mass, that they are regarded as mere accessory though undoubtedly original ingredients.[1] Again, in rocks of igneous origin, such as modern lava, the essential ingredients cannot be traced back further than the eruption of the mass containing them. They are not only original as constituents of the lava, but are themselves original and non-derivative minerals, produced directly from the crystallization of molten minerals ejected from beneath the earth's crust, though, as Michel Lévy has shown, the débris of older minerals may sometimes be traced amidst the later crystals of massive rocks.[2] In rocks of aqueous origin, however, there are many, such as conglomerates and sandstones, where the component minerals, though original ingredients of the rocks, are evidently of derivative origin. The little quartz granules of a sandstone have formed part of the rock ever since it was accumulated, and are its essential constituents. Yet each of these once formed part of some older rocks, the destruction of which yielded materials for the production of the sandstone.

The same mineral may occur both as an original and as a secondary constituent. Quartz, for example, appears everywhere in both conditions; indeed, it may sometimes be found in the twofold form even in the same rock, though there is then usually some difference between the original and secondary quartz. A quartz-felsite, for instance, abounds in original little kernels, or in double

[1] Some of the "accessory" minerals, however, may be of great importance as indicative of the conditions under which the rock was formed.

[2] *Bull. Soc. Géol. France*, 3rd ser. iii. 199. See also Fouqué et Michel Lévy, "Minéralogie Micrographique," p. 189.

pyramids of the mineral often enclosing fluid cavities, while the secondary or accidental forms occur in veins, reticulations, or other irregular aggregates, distinguished by a peculiar chequered structure in polarized light, and by an absence of the crowded cavities so characteristic in the quartz of igneous rocks.

Accessory minerals frequently occur in cavities where they have had room to crystallize out from the general mass. The "drusy" cavities or open spaces lined with well developed crystals found in some granites are good examples, for it is there that the non-essential minerals are chiefly to be recognized. The veins of segregation found in many crystalline rocks, particularly in those of the granitic series, are further illustrations of the original separation of mineral ingredients from the general magma of a rock (see p. 132). In some cases minerals assume a concretionary shape, which may be observed chiefly though not entirely in rocks formed in water. Some minerals are particularly prone to occur in concretions. Siderite or ferrous carbonate is to be found in abundant nodules mixed with clay and organic matter among consolidated muddy deposits. Calcite or calcium carbonate is likewise abundantly concretionary. Silica in the forms of chert and flint appears in irregular concretions, in old calcareous formations, composed mainly of the remains of marine organisms.

Secondary minerals have been developed as the result of subsequent changes in rocks, and are almost invariably due to the chemical action of percolating water, either from above or from below. Occurring under circumstances in which such water could act with effect, they are found in cracks, joints, fissures, and other divisional planes and cavities of rocks. These subterranean channels, frequently several feet or even yards wide, have been gradually filled up by the deposit of mineral matter on their sides (see the Section on Mineral Veins). The cavities formed by expanding steam in ancient lavas (amygdaloids) have offered abundant opportunities for deposits of this kind. They have accordingly been in large measure occupied by secondary minerals (amygdules), such as calcite, calcedony, quartz and zeolites.

In the succeeding description of the more important rock-forming minerals, attention will be drawn to physical characters, such as crystalline form, hardness[1] (H.), and specific gravity (Gr.); chemical composition; modes of occurrence, whether original or secondary; and modes of origin, whether igneous, aqueous, or organic; pseudomorphs, that is, the various minerals which any given mineral has replaced, while retaining their external forms, and likewise those which are found to have supplanted the mineral in question while in the same way retaining its form—a valuable clue to the internal

[1] The scale of hardness in use among mineralogists is divided into ten degrees, each denoted by the name of some mineral: 1. Talc. 2. Rock-salt. 3. Calcite. 4. Fluor-spar. 5. Apatite. 6. Orthoclase. 7. Quartz. 8. Topaz. 9. Corundum. 10. Diamond. A mineral which is scratched with the same ease as quartz is said to have H. 7; a mineral which scratches fluor-spar, but is scratched by apatite, is between H. 4 and H. 5.

chemical changes which rocks undergo from the action of percolating water (Book III. Part II. Section ii., § 1 and 2); and lastly, characteristics or peculiarities of weathering, where any such exist that deserve special mention.

The native elements are comparatively of rare occurrence, and only two of them, carbon and sulphur, occasionally play the part of noteworthy essential and accessory constitutents of rocks. A few of the native metals, more specially copper and gold, now and then appear in sufficient quantity to constitute commercially important ingredients of veins and rock-masses.

Graphite.—Rarely crystallized in hexagonal forms, usually granular, scaly, or compact. H. 0·5—1·0. Gr. 1·9—2·3. Nearly pure carbon, but generally with at least 1 or 2 per cent. of silica, lime, iron, or other impurity. Under the microscope, opaque; appearing velvet-black with reflected light. Found chiefly in ancient crystalline rocks, as gneiss, mica-schist, granite, &c.; some of the Laurentian limestones of Canada being so full of the diffused mineral as to be profitably worked for it; in rare instances coal has been observed changed into it by intrusive basalt (Ayrshire). Probably in most cases the result of the alteration of imbedded organic matter, especially remains of plants; occasionally observed as a pseudomorph after calcite and pyrites, and sometimes enclosing sphene and other minerals.[1]

Graphite is little affected by percolating water, hence it is not a replacement mineral. But Vom Rath has described an example from Westphalia where calcite has been partially replaced externally by an encrusting pseudomorph of graphite.[2]

Sulphur.—Crystallized in rhombic pyramids; but more commonly compact, granular, powdery, stalactitic, or incrusting. H. 1·5—2·5. Gr. 1·9—2·1. Normally pure sulphur, but often much mixed with earthy, calcareous, or bituminous impurities. Occurs under two conditions. 1st, as a product of volcanic action in the vents and fissures of active and dormant cones. Volcanic sulphur is formed from the oxidation of the sulphuretted hydrogen, so copiously emitted with the steam that issues from volcanic vents, as at the Solfatara, near Naples. It may also be produced by the mutual decomposition of the same gas and anhydrous sulphuric acid. 2nd, in beds and layers or diffused particles resulting from the alteration of previous minerals, particularly sulphates, or from deposit in water through decomposition of sulphuretted hydrogen. The frequent crystallization of sulphur shows that the mineral must have been formed at ordinary temperatures, for its natural crystals melt at 238·1° Fahr. Its formation may be observed in progress at many sulphureous springs, where it falls to the bottom as a pale mud through the oxidation of the sulphuretted hydrogen in the water. It occurs in Sicily, Spain and elsewhere, in beds of bituminous

[1] Vom Rath. *Sitzungsber. Wien. Akad.* x. p. 67; Sullivan in Jukes' *Manual of Geology*, 3rd edit. p. 56.
[2] *Neues Jahrb. Min.* 1874, p. 522.

limestone and gypsum. These strata, sometimes full of remains of fresh-water shells and plants, are interlaminated with sulphur, the very shells being not infrequently replaced by this mineral. Here the presence of the sulphur may be traced to the reduction of the calcium sulphate to the state of sulphide through the action of the decomposing organic matter, and the subsequent production and decomposition of sulphuretted hydrogen, with consequent liberation of sulphur.[1] The sulphur deposits of Sicily furnish an excellent illustration of the alternate deposit of sulphur and limestone. They consist mainly of a marly limestone, through which the sulphur is partly disseminated and partly interstratified in thin laminæ and thicker layers, some of which are occasionally 28 feet deep. Below these deposits lie older Tertiary gypseous formations, the decomposition of which has probably produced the deposits of sulphur in the overlying more recent lake-basins.[2]

The weathering of sulphur is exemplified on a considerable scale at these Sicilian deposits. The sulphur, in presence of limestone, oxygen, and moisture, becomes sulphuric acid, which combining with the limestone forms gypsum, a curious return to what was probably the original substance from the decomposition of which the sulphur was derived. Hence the site of the outcrop of the sulphur beds is marked at the surface by a white earthy rock, or *borscale*, which is regarded by the miners in Sicily to be a sure indication of sulphur underneath, as the gossan of Cornwall is indicative of underlying metalliferous veins.[3]

Iron.—This most important of all the metals has hitherto been found only sparingly in the native state. It occurs in grains and blocks which have fallen from planetary space as meteorites. Nordenskiold describes fifteen blocks of iron on the island of Disco, Greenland, the weight of the two largest being 21,000 and 8,000 kilogrammes (11·8 and 7·9 tons) respectively. Numerous smaller pieces have been picked up in most parts of the world; fine grains or dust of similar iron have been observed in hailstones and in snow of the Alps, Sweden and Siberia, and by Mr. Murray of the *Challenger* on the ocean floor at remote distances from land. There can be no doubt that a small but constant supply of native iron is falling upon the earth's surface from outside the terrestrial atmosphere.[4] This iron is alloyed with nickel, and contains small quantities of cobalt, copper and other ingredients. Dr. Andrews, however, showed in 1852 that native iron in minute spicules or granules exists in some basalts and other volcanic rocks,[5] and Mr. J. Y. Buchanan has recently detected it in appreciable quantity in the gabbro of the West of Scotland. It occurs also in

[1] Braun, *Bull. Soc. Géol. France*, 1st ser. xii. p. 171.
[2] *Memorie del R. Comitato Geologico d'Italia*, i. (1871).
[3] *Journ. Soc. Arts*, 1873, p. 170.
[4] See Ehrenberg, *Frorieps Notizen*, Feb. 1846; Nordenskiöld, *Comptes-rendus Acad. Sci.* lxxvii. p. 463, lxxviii. p. 236. Tissandier, *op. cit.* lxxviii. p. 821, lxxx. p. 58, lxxxi. p. 576. See lxxv. (1872) p. 683. Yung, *Bull. Soc. Vaudoise, Sci. Nat.* (1876), xiv. p. 493.
[5] *Brit. Assoc. Rep.* 1852.

basalts of Bohemia and Greenland. Nordenskiöld observed that at the same locality in Disco Island, where he found the large blocks of native iron, the underlying basalt contained lenticular and disc-shaped blocks of precisely similar iron. He infers that the whole of the blocks may belong to a meteoric shower which fell during the time (Tertiary) when the basalt was poured out at the surface. He dismisses the suggestion that the iron could possibly be of telluric origin.[1] But the microscope reveals in this basalt the presence of minute particles of native iron which, associated with viridite, are moulded round the crystals of labradorite and augite.[2] Daubrée appears therefore to be justified in regarding this iron as derived from the inner metallic portions of the globe which lie at depths inaccessible to our observations, but from which, on his view, the vast Greenland basalt-eruptions have brought up traces to the surface.[3]

In the great majority of cases the Oxides occur combined with some acid. A few uncombined take a prominent place as essential constituents or frequent ingredients of rocks.

SILICA is found in three forms, Quartz, Tridymite, and Opal.

Quartz occurs either (1) crystallized in clear hexagonal prisms (rock-crystal, amethyst, cairngorm), also opaque or translucent, granular, crystalline (common quartz, vein quartz), or (2) non-crystalline, crypto-crystalline, or compact (calcedony, hornstone, jasper), often coloured with iron or other impurity. $Si\ O_2 = Si\ 46{\cdot}67$, $O\ 53{\cdot}33$. H. = 7. Gr. 2·5—2·8. Calcedony includes translucent, compact, non-crystalline minerals occurring in stalactitic or encrusting forms, and in nodules and layers: regarded as intimate mixtures of amorphous (soluble in caustic potass) and crystalline silica.

Quartz is abundant as (1) an essential constituent of rocks, as in granite, (p. 131), gneiss, mica-schist, quartz-trachyte, quartz-porphyry, sandstone; (2) an accessory ingredient filling wholly or partially veins, joints, cracks and cavities. It has been produced from (*a*) igneous action, as in volcanic rocks; (*b*) aquo-igneous or plutonic action, as in granites, gneisses, &c.; (*c*) solution in water, as where it lines cavities or replaces other minerals. The last mode of formation is that of the crystalline and non-crystalline quartz and calcedony found as secondary ingredients in rocks.

The study of the endomorphs and pseudomorphs of quartz is of great importance in the investigation of the history of rocks. No mineral is so conspicuous for the variety of other minerals enclosed within it. In some secondary quartz crystals each prism forms a small mineralogical cabinet enclosing a dozen or more distinct minerals, as rutile, hæmatite, limonite, pyrites, chlorite, and many others.[4] Quartz may be observed replacing calcite, aragonite,

[1] *Geol. Mag.* ix. [2] Fouqué et Michel-Lévy, *op. cit.* p. 443.
[3] Daubrée, *Discours, Acad. Sciences.* 1 March, 1880, p. 17. See also W. Flight in *Geol. Mag.* ii. (2nd ser.) p. 152.
[4] See Sullivan, in Jukes' *Manual*, p. 61.

siderite, gypsum, rock-salt, hæmatite, &c. This facility of replacement constitutes silica one of the most valuable petrifying agents in nature. Organic bodies which have been silicified retain often with the utmost perfection their minutest and most delicate structures.

The student can usually detect quartz by its external characters, and especially by its vitreous lustre and hardness. When in the form of minute blebs or crystals, it may be recognised in many rocks with a good lens. Under the microscope it presents a characteristic brilliant chromatic polarization, with no trace of any alteration of its borders; while calcedony displays a minute concentric radial structure giving a black cross between crossed Nicols. Where it is an original and essential constituent of a rock quartz it very commonly contains minute rounded or irregular cavities or pores partially filled with liquid. So minute are these cavities that a thousand millions of them may, when they are closely aggregated, lie within a cubic inch. The liquid is chiefly water, not uncommonly containing sodium chloride or other salt, sometimes liquid carbon dioxide and hydro-carbons.[1]

Rock crystal and crystalline quartz resist atmospheric weathering with great persistence. Hence the quartz grains may usually be easily discovered in the weathered crust of a quartziferous igneous rock. But corroded quartz crystals have been observed in exposed mountainous situations, with their edges rounded and eaten away.[2] The non-crystallized forms of silica are more easily affected. Flint and many forms of coloured calcedony weather with a white crust. But it is chiefly from the weathering of silicates (especially through the action of organic acids) that the soluble silica of natural waters is derived. Book III. Part II. Section ii. § 7.

Tridymite, in minute hexagonal tables (belonging according to von Lasaulx to the triclinic system), often somewhat rounded, and almost always grouped in twins, or still more in trins (hence the name), which are aggregated round and upon each other, has been met with chiefly among volcanic rocks (trachytes, andesites, &c.), both as an abundant constituent of those which have been poured out in the form of lava, and also in the ejected blocks of Vesuvius.[3]

Opal—the hydrated form of silica; amorphous, subtranslucent to opaque, containing 3 to 13 per cent. of water, with variable admixture of iron oxides, lime, magnesia, alumina, and alkalies. H. 5·5—6·5. Gr. 1·9—2·3. The opals have been formed from solution in water, or from the hydration of anhydrous silica. Noble opal, fire opal, common opal, and semi-opal are usually disseminated in veins and nests through rocks. Semi-opal occasionally replaces the original

[1] See Brewster, *Trans. Roy. Soc. Edin.* x. p. 1. Sorby, *Quart. Journ. Geol. Soc.* xiv. p. 453. *Proc. Roy. Soc.* xv. p. 153; xvii. p. 299. Zirkel, *Mikroskopische Beschaffenheit der Mineralien und Gesteine*, p. 39. Rosenbusch, *Mikroskopische Physiographie*, i. p. 30. Hartley, *Journ. Chem. Soc.* February, 1876. The occurrence of fluid cavities in the crystals of rocks is more fully described in Part II. § iv. of this Book.

[2] Roth. *Chem. Geol.* i. p. 94.

[3] Vom Rath. *Z. Deutsch. Geol. Ges.* xxv. p. 236, 1873.

substance of fossil wood (wood-opal). Several forms of opal are deposited by geysers, and are known under the general appellation of sinters. Hydrated silica appears likewise as the result of plant and animal growth in tripoli powder, randanite, and other earths which are composed mainly or wholly of the remains of diatoms, &c.

Corundum occurs in clear rhombohedral forms (sapphire and ruby); also in dull, coarse, feebly translucent crystals (corundum), and in an amorphous granular form mixed with iron oxide (emery). H. 9. Gr. 3·9—4. Alumina or aluminic oxide, $Al_2 O_3 = Al\ 53{\cdot}2\ O\ 46{\cdot}8$. Found in crystalline rocks, particularly in certain serpentines and schists, gneiss, granite, dolomite, and rocks of the metamorphic series. The largest deposits of corundum yet known occur in the eastern states of America, from Massachusetts to Alabama. One of these runs for four miles, with a thickness of four feet, in a talcose slate and serpentine between gneiss and mica-slate in the centre of the Green Mountains. The occurrence of such enormous masses of alumina has been pointedly dwelt upon by Dr. F. A. Genth, who has brought to light a remarkable series of transformations of corundum into other minerals, among which are spinel, zoisite, felspars, tourmaline, fibrolite, cyanite, chlorite, lazulite, and the micas known as damourite and margarite.[1] He affirms that large beds of corundum associated with the deposition of chromiferous chrysolite beds (since altered into serpentine) have been subsequently acted upon in such a way as to be converted into the minerals just mentioned, and that a portion of the altered products remains as large beds of mica- and chlorite-slates or schists. The difficulty of explaining how such alterations could take place in a substance which in our laboratories so resists solution, he has not yet been able to solve.[2] Corundum (sapphire and ruby) has been formed artificially.

IRON OXIDES.—Four minerals, composed mainly of iron oxides, occur abundantly as essential and accessory ingredients of rocks. Hæmatite, Limonite, Magnetite, and Titanic iron.

Hæmatite (Fer oligiste, Rotheisen, Eisenglanz) occurs crystallized in rhombohedral forms with splendent metallic lustre (specular iron) but most commonly in compact or crypto-crystalline, usually fibrous, sometimes amorphous aggregations (red iron), with cherry-red streak. H. 5·5—6·5. Gr. 5·19—5·28. Ferric oxide, sesquioxide or peroxide of iron, $Fe_2 O_3 = Fe\ 70,\ O\ 30$. In the crystallized form the mineral occurs in veins as well as lining cavities and fissures of rocks. The fibrous and more common form (which often has portions of its mass passing into the crystallized condition) lies likewise in strings or veins; also in cavities, which, when of large size, have given opportunity for the deposit of great masses of hæmatite, as in

[1] *American Phil. Soc.* 1873.

[2] But of the reality of some of the remarkable metamorphisms he describes, the present writer can speak with the confidence arising from a personal inspection of the proofs with which Dr. Genth favoured him at the Laboratory of the University of Pennsylvania in October, 1879.

cavernous limestones (Westmoreland). It occurs with other ores and minerals as an abundant component of mineral veins, likewise in beds interstratified with sedimentary or schistose rocks. Scales and specks of opaque or clear bright red hæmatite, of frequent occurrence in the crystals of rocks, give them a reddish colour or peculiar lustre (perthite, stilbite). Under the microscope hæmatite is dull red or opaque, distinguishable from magnetite by crystallographic form and colour. It appears abundantly as a product of sublimation in the clefts of volcanic cones and lava streams. In veins and beds among rocks it is probably in most cases a deposition from water, resulting from the alteration of some previous soluble combination of the metal, frequently the oxidation of the carbonate. It is found pseudomorphous after ferrous carbonate, and this has probably been the origin of beds of red ochre occasionally intercalated among stratified rocks. It likewise replaces calcite, dolomite, quartz, barytes, pyrites, magnetite, rock-salt, fluor-spar, &c.

Limonite (brown iron ore) occurs in no definite crystallized form, but in finely fibrous or indistinctly crystalline, mammillated, encrusting, or stalactitic aggregates, often earthy and amorphous; blackish brown to ochre yellow, with yellowish brown streak. H. 5. Gr. 3·4—3·95. Consists of hydrous ferric oxide, $Fe_2O_3+3H_2O = Fe_2O_3$ 85·56, H_2O 14·44. Occurs in beds among stratified formations, and may be seen in the course of deposit through the action of organic acids in marsh land (bog iron ore) and lake-bottoms. (Book IV. Part II. Section iii.) In the form of yellow ochre it is precipitated from the waters of chalybeate springs containing green vitriol derived from the oxidation of iron sulphides.[1] Limonite is a common decomposition product in rocks containing iron among their constituents. It is thus always a secondary or derivative substance resulting from chemical alteration.

The pseudomorphous forms of limonite show to what a large extent iron oxides are carried in solution through rocks. The mineral has been found replacing calcite, siderite, dolomite, hæmatite, magnetite, pyrite, marcasite, galena, blende, gypsum, barytes, fluor-spar, pyroxene, quartz, garnet, beryl, &c.

Magnetite (Fer oxydulé, Magneteisen), isometric, abundant in octohedral forms, in crystallites, and in minute irregular grains; also massive. Strongly magnetic. Black, with a semi-metallic lustre, and subconchoidal fracture. H 5·5—6·5. Gr. 4·9—5·2. Ferroso-ferric oxide—a mixture of ferrous oxide (FeO 31·03) and ferric oxide (Fe_2O_3 68·97) or Fe 72·41; O 27·59, but often containing titanic acid or magnesia. Soluble in hydrochloric acid. Under the microscope distinguishable by its intense opacity, and by its blue black colour with reflected light.

Occurs abundantly in some schists, particularly in chlorite-slate and talc-slate in scattered octohedral crystals sometimes of consider-

[1] Sullivan, *op. cit.* p. 63.

able size; in other schists and in crystalline massive rocks like granite, in diffused grains or minute crystals; also found in massive beds among schists and gneisses, as in Norway and in the eastern states of North America. One of the essential ingredients of basalt and other volcanic rocks, being there present in minute octohedral crystals, or in granules or crystallites. Likewise found as a pseudomorphous secondary product resulting from the alteration of some previous mineral, as hæmatite, pyrite, quartz, hornblende, augite, garnet and sphene. This mineral may thus result from either aqueous or igneous action. It has likewise been observed with hæmatite, &c., as a product of sublimation at volcanic foci where chlorides of the metals in presence of steam are resolved into hydrochloric acid and anhydrous oxides.

Magnetite is liable to weather by the reducing effects of decomposing organic matter, whereby it becomes a carbonate and then by exposure passes into the hydrous or anhydrous peroxide. The magnetite grains of basalt rocks are very generally oxidised at the surface, and sometimes even for some depth inward. Michel-Lévy has observed them to be enveloped in biotite.[1]

Titanic Iron (Titaniferous Iron, Menaccanite, Ilmenite, Fer titané, Titaneisen), distinguished from magnetite by its rhombohedral crystallization, occurs frequently in thin plates or tables, as well as in diffused grains. H. 5—6. Gr. 4·5—5·2. A mixture of oxides of iron and titanium in considerably variable proportions, being sometimes an isomorphous mixture of titanic acid and ferrous oxide; sometimes with the addition of ferric oxide, or with that of magnesium titanate. Scarcely to be distinguished from magnetite when seen in small particles under the microscope, but possessing a brown semi-metallic lustre with reflected light; resists corrosion by acids when the powder of a rock containing it is exposed to their action, while magnetite is attacked and dissolved. Occurs in scattered grains, plates, and crystals as an abundant constituent of many crystalline rocks (basalt rocks, diabase, gabbro, and other igneous masses); also in veins or beds in syenite, serpentine, and metamorphic rocks. Some of the Canadian masses of this mineral are 90 feet thick and many yards in length.

Titanic iron frequently resists weathering, so that its black glossy granules long project from a weathered surface of rock. In other cases it is decomposed either by oxidation of its protoxide, when the usual brown or yellowish colour of the hydrous ferric oxide appears, or by removal of the iron. The latter is believed to be the origin of a peculiar milky white opaque substance, frequently to be observed under the microscope, surrounding and even replacing crystals of titanic iron, and named Leucoxene by Gümbel.[2]

MANGANESE OXIDES are frequently associated with those of iron

[1] *Bull. Soc. Géol. France*, 3rd ser. vi. p. 164.

[2] *Die paläolitische Eruptivgesteine des Fichtelgebirges*, 1874, p. 29. See Rosenbusch, *Mik. Physiog.* ii. p. 336. De la Vallée Poussin and Renard, *Mem. Couronnées Acad. Roy. de Belgique*, 1876, xl. Planche, vi. pp. 34 and 35. Fouqué et Michel-Lévy, *op. cit.* p. 426.

in ordinary rock-forming minerals, but in such minute proportions as to have been generally neglected in analyses. Their presence in the rocks of a district is sometimes shown by deposits of the hydrous oxide in the forms of psilomelane and wad. These deposits sometimes take place as black or dark brown branching, plant-like or *dendritic* impressions between the divisional planes of close-grained rocks (limestone, felsite, &c.) sometimes as accumulations of a black or brown earthy substance in hollows of rocks, and occasionally as deposits in marshy places, like those of bog iron ore.

Silicates.—These embrace by far the largest and most important series of rock-forming minerals. Their chief groups are the anhydrous aluminous and magnesian silicates embracing the Felspars, Hornblendes, Augites, Olivines, Micas, &c., and the hydrous silicates which include the Zeolites, Clays, talc, chlorite, serpentine, &c.

The family of the Felspars forms one of the most important of all the constituents of rocks, seeing that its members constitute by much the largest portion of the plutonic and volcanic rocks; are abundantly present among many crystalline schists, and by their decay have supplied a great part of the clay out of which argillaceous sedimentary formations have been constructed.

The felspars are usually divided into two series. 1st, The orthoclastic or monoclinic felspars, consisting of two species or varieties, Orthoclase and Sanidine; and 2nd, The plagioclastic or triclinic felspars, among which, as constituents of rocks, may be mentioned the species albite, anorthite, oligoclase, andesine, labradorite, and microcline.

Orthoclase, monoclinic, commonly in twins of the Carlsbad form, the suture of which can often be seen with the naked eye on the abundant and perfect cleavage planes; occurs in well developed crystals in many porphyritic rocks, also in the drusy cavities of granites; but more frequently, as a constituent of rocks, presents incomplete crystals, and even more or less rounded or irregular crystalline forms. Colourless, but more usually white, grey, or pink, the sanidine being clear and glassy, the orthoclase somewhat turbid. Normal composition, Silica 64·6, alumina 18·5, potash 16·9, but with small and variable proportions of lime, iron, magnesia and soda; scarcely affected by acids. Under the microscope recognizable from quartz by its characteristic cleavage, twinning, turbidity, and frequent alteration.[1] A peculiar lattice-like network of interlacing lines, or a fine parallel striping, may be observed on a fresh cleavage face of some varieties of orthoclase, such as that of the well known red granite of Upper Egypt. This must not be confounded with the characteristic lamellation of the triclinic felspars. It appears to arise in many cases, if not always, from the crystallization together of parallel or intersecting laminæ of some other felspar (albite for example) with the orthoclase.

[1] On microscopic determination of felspars, see Fouqué et Michel-Lévy *op. cit.* pp. 209, 227.

Orthoclase occurs abundantly as an original constituent of many crystalline rocks (granite, syenite, felsite, gneiss, &c.), likewise in cavities and veinings in which it has segregated from the surrounding mass (pegmatite). It is seldom found in unaltered sedimentary rocks except in fragments derived from older crystalline masses. It is generally associated with quartz, and often with hornblende, while the felspars less rich in silica more rarely accompany free quartz. Orthoclase is both an original constituent of plutonic and old volcanic rocks (granite, felsite, &c.), and a result of the metamorphism of sedimentary materials into foliated masses of gneiss and various schists. A few examples have been noticed where orthoclase has replaced other minerals (prehnite, analcime, laumontite).

Orthoclase weathers on the whole with comparative rapidity, though durable varieties are known. The alkali and some of the silica are removed, and the mineral passes into clay or kaolin (p. 81).

Sanidine. Under this name is comprised the clear glassy fissured variety of orthoclase which forms so conspicuous an ingredient in the more silicated Tertiary and modern lavas. It has the same composition as orthoclase, but often with a rather higher percentage of soda. It occurs in some trachytes in large flat tables (hence the name "sanidine"); more commonly in fine clear or grey crystals or crystalline granules, and sometimes in a vitreous condition (obsidian). It is an eminently volcanic mineral. In many lavas its large crystals are generally broken, indicative of their having already crystallized out before the lava ceased to flow; they may frequently be found full of enclosures or microliths of other minerals.

Plagioclase, or Triclinic Felspars.—While the different felspars which crystallize in the triclinic system may be more or less easily distinguished in large crystals or crystalline aggregates, they are difficult to separate in the minute forms in which they commonly occur as rock constituents. They have been grouped by petrographers under the general name Plagioclase (with oblique cleavage) proposed by Tschermak, who regards them as mixtures in various proportions of two fundamental compounds—albite or soda-felspar, and anorthite or lime-felspar.

They occur mostly in well developed crystals, partly in irregular crystalline grains, and sometimes as a crystalline paste or base in which the other crystals of the rock are imbedded. On a fresh fracture their crystals appear as clear glassy strips, on which may usually be detected a fine parallel lineation or ruling, indicating a characteristic polysynthetic twinning which never appears in orthoclase. A felspar striated in this manner can thus be at once pronounced to be a triclinic form, though the distinction is not invariably present. Under the microscope the fine parallel lamellation seen with polarized light forms one of the most distinctive features of this group of felspars.

The following table shows the average composition of the chief triclinic felspars.

		Silica.	Alumina.	Potash.	Soda.	Lime.	Hardness.	Spec. Gravity.	Habitat.
Potash Felspar	Microcline	64·30	19·70	15·60	0·48	..	6·0	2·540	In some syenites, &c.
Soda felspar.	Albite . .	68·62	19·56	..	11·82	..	6—6·5	2·59—2·64	In some granites, and in several volcanic rocks.
Soda-lime and Lime-soda felspars.	Oligoclase	63·70	23·95	1·20	8·11	2·05	6·0	2·60—2·66	In many granites and other eruptive rocks.
	Andesine .	63·85	24·05	0.88	5.01	5·04	5—6	2·66—2·69	In some syenites, &c.
	Labradorite	52·90	30·30	..	4·50	12·30	6·0	2·68—2·74	Essential constituent of many lavas, &c., abundant in masses in azoic rocks of Canada, &c.
Lime-felspar.	Anorthite.	43·08	36·82	..	..	20·10	6·0	2·67—2·76	In many volcanic rocks, sometimes in granites and metamorphic rocks.

The triclinic felspars have been produced sometimes directly from igneous fusion. This can be studied in many lavas, where one of the first minerals to appear in the devitrification of the original molten glass is the labradorite or other plagioclase. In other cases these minerals have resulted from the operation of the processes to which the formation of the crystalline schists was due; large beds as well as abundant diffused strings, veinings, and crystals of triclinic felspar (labradorite) form a marked feature among the ancient gneisses of Eastern Canada. The more highly silicated species (albite, oligoclase) occur with orthoclase as essential constituents of many granites and other plutonic rocks. The more basic forms (labradorite, anorthite) are generally absent where free silica is present; but occur in the more basic igneous rocks (basalts, &c.).

Considerable differences are presented by the triclinic felspars in regard to weathering. On an exposed face of rock they lose their glassy lustre and become white and opaque. This change, as in orthoclase, arises from loss of bases and silica and from hydration. Traces of carbonates may often be observed in weathered crystals. The original steam cavities of old volcanic rocks have generally been filled with infiltrated minerals, which in many cases have resulted from the weathering and decomposition of the triclinic felspars. Calcite, prehnite, and the family of zeolites have been abundantly produced in this way. The student will usually observe that where these minerals abound in the cells and crevices of a rock, the rock itself is for the most part proportionately decomposed, showing the relation that subsists between these infiltration products and the decomposition of the surrounding mass. Abundance of calcite in veins and

cavities of a felspathic rock affords good ground for suspecting the presence in the latter of a lime-felspar.[1]

Saussurite, a compact, finely granular, not definitely crystallized, greyish to greenish-white, faintly translucent to opaque mineral, having an average composition of silica 43—49, alumina 25—32 per cent., with variable proportions of lime and soda. H. 6—7. Gr. 3·22—3·43. It forms with diallage some varieties of gabbro, and is abundantly associated with labradorite, or with hornblende in others. Under the microscope it presents a confused aggregate of crystalline needles and granules imbedded in an amorphous glass-like matrix.

THE MICA FAMILY embraces a number of minerals now referred to the monoclinic system, distinguished especially by their very perfect basal cleavage, whereby they can be split into remarkably thin elastic laminæ, and by a predominant splendent pearly lustre. They consist essentially of silicates of alumina and potash or magnesia, usually with some oxide of iron, but little or no lime, and are in some varieties distinctly hydrous.

Muscovite (Potash-mica, Glimmer) in silvery white (also greenish and brownish) tables or irregular scales, capable of being split into thin transparent laminæ with a pearly lustre. H. 2—3. Gr. 2·8—3·1. The proportion of silica ranges between 45 and 50 per cent., alumina from 26 to 36, potash from 6 to 10, soda from 0 to 1·5, water from 1 to 4·7. There is usually also a small percentage of fluorine. Abundant as an original constituent of many crystalline rocks (granite, &c.), and as one of the characteristic minerals of the crystalline schists; also in many sandstones where its small parallel flakes, derived like the surrounding quartz grains from older crystalline masses, impart a silvery or "micaceous" lustre and fissility to the stone. Under the microscope thin plates of muscovite give bright chromatic polarization when cut parallel to the basal cleavage. But as the sections of the mineral displayed in a thin slice of any rock rarely coincide with the cleavage, but traverse it at various angles, they appear usually as narrow bands with fine parallel lines which mark the planes of cleavage.[2]

The persistence of muscovite under exposure to weather is shown by the silvery plates of the mineral, which may be detected on a crumbling surface of granite or schist where most of the other minerals, save the quartz, have decayed; also by the frequency of the micaceous lamination of sandstones.

Lepidolite (Lithia-mica), usually in scaly aggregates of a delicate violet colour; generally resembles muscovite, containing 49—52 per cent. of silica, 26·7—28·5 of alumina, about 10 of potash, 1—6 of lithia, and 2—8 of fluorine. Occurs in some granites and crystalline schists, especially in veins.

[1] A valuable essay on the stages of the weathering of triclinic felspar as revealed by the microscope was published by G. Rose in 1867. *Zeitsch. Deutsch. Geol. Ges.* xix. p. 276.

[2] On the microscopic determination of the micas, see Fouqué et Michel-Lévy, *op. cit.* p. 333.

Damourite is merely a variety of muscovite with about 5 per cent. of water. It occurs among crystalline schists, and is regarded by Genth as one of the products of the alteration of corundum.

Sericite, a talc-like variety of muscovite occurring in soft inelastic scales in some schists.

Margarodite, a silvery, talc-like hydrous mica, which appears to have resulted from the hydration of muscovite, and to be widely diffused as a constituent of granite and other crystalline rocks.

Paragonite, a scaly micaceous mineral forming the main mass of certain alpine schists; it is a hydrous soda mica (containing 6—8·45 per cent. of soda).

Biotite (Magnesia mica) occurs in six-sided plates or irregularly defined scales, usually dark coloured (green, grey, brown to black) with pearly lustre on the basal cleavage planes. H. 2·5—3. Gr. 2·74—3·13. Composition variable, but marked by the occurrence of 10 to 30 per cent. of magnesia. Occurs abundantly as an original constituent of many granites, gneisses, and schists; also sometimes in basalt, trachyte, and as ejected fragments and crystals in tuff. Its small scales, when cut transverse to the dominant cleavage, may usually be detected under the microscope by their remarkably strong dichroism, their fine parallel lines of cleavage, and their frequently frayed appearance at the ends.

Biotite under the action of the weather assumes a pale, dull, soft crust, owing to removal of its bases. The mineral *rubellan*, which occurs in hexagonal brown or red opaque inelastic tables in some basalts and other igneous rocks, is regarded as an altered form of biotite.

Hornblende (Amphibole). Monoclinic, in short stout or long slender prisms; also in bladed forms and needles, generally of a dark green or black colour (sometimes white). H. 5—6. Gr. 2·9—3·3. Divided into two groups. 1st. Non-aluminous, consisting mainly of meta-silicates of magnesium and calcium, with 55 to 59 per cent. of silica, 21 to 27 magnesia, 11 to 15 lime, and minor proportions of the protoxides of iron and manganese. These include the white and pale green or grey fibrous varieties (tremolite, actinolite, anthophyllite, &c.). 2nd. Aluminous, containing silica 39—49, magnesia 10—20, alumina 8—15, lime 10—15, ferrous and ferric oxides sometimes up to more than 20 per cent. These embrace the more abundant dark green, brown, or black varieties. Under the microscope hornblende presents cleavage angles of 124° 30′, the definite cleavage planes intersecting each other in a well-marked lattice work, sometimes with a finely fibrous character superadded. It also shows a marked pleochroism with polarized light, which, as Tschermak first pointed out, usually distinguishes it from augite.[1]

The pale non-aluminous hornblendes are found among gneisses, crystalline limestones, and other metamorphic rocks. The dark varieties, though also found in similar situations, sometimes even

[1] Acad. Wien, May 1869. See also Fouqué et Michel-Lévy, *op. cit.* pp. 349, 365.

forming entire masses of rock (hornblende-rock, hornblende-schist), are the common forms in granitic and volcanic rocks (granite, syenite, diorite, andesite, &c.) The former group naturally gives rise by weathering to various hydrous magnesian silicates, notably to serpentine and talc. In the weathering of the aluminous varieties, silica, lime, magnesia and a portion of the alkalies are removed with conversion of part of the earths and the iron into carbonates. The further oxidation of the ferrous carbonate is shown by the yellow and brown crust so commonly to be seen on the surface or penetrating cracks in the hornblende. The change proceeds until a mere internal kernel of unaltered mineral remains, or until the whole has been converted into a ferruginous clay.

Augite (Pyroxene). Monoclinic, chiefly in short stout prisms; also granular, more rarely lamellar or fibrous; ranging from white through shades of green to black. H. 5—6. Gr. 2·88—3·5. Divided like hornblende into two groups. 1st. Non-aluminous, CaMg $2SiO_3$, consisting of meta-silicates of magnesium and calcium (silica 49 to 56

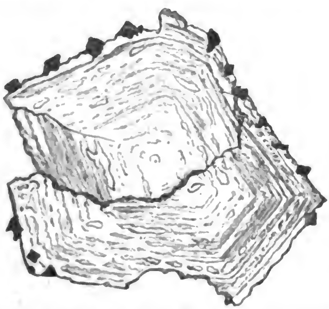


FIG. 5.—SECTION OF AN AUGITE CRYSTAL FROM A BASALT-DYKE, CRAWFORDJOHN, LANARKSHIRE, MAGNIFIED, SHOWING LINES OF GROWTH, WITH VESICLES, AND MAGNETITE CRYSTALS.

per cent.), usually with a little protosilicate of iron (very commonly also of manganese), which gives the prevalent green colour to the group (malacolite, sahlite, &c.). 2nd. Aluminous (silica 47 to 55 per cent., alumina 4 to 9 per cent., with a small variable proportion of ferrous oxide), including generally the dark green or black varieties (common augite, fassaite). It would appear that the substance of hornblende and augite is dimorphous, for the experiments of Berthier, Mitscherlich and G. Rose showed that hornblende, when melted and allowed to cool, assumed the crystalline form of augite. Whence it has been inferred that hornblende is the result of very slow, and augite of comparatively rapid cooling.

Under the microscope augite in thin slices is only very feebly pleochroic, and presents cleavage lines intersecting at an angle of 87° 5′.

It is often remarkable for the amount of extraneous materials enclosed within its crystals. Like some felspars, augite may be found in basalt with merely an outer casing of its own substance, the core being composed of magnetite, of the ground-mass of the surrounding rock, or of some other mineral (Fig. 5).

The distribution of augite resembles that of hornblende; the pale, non-aluminous varieties are more specially found among gneisses, marbles, and other crystalline, foliated, or metamorphic rocks; the dark green or black varieties enter as essential constituents into many igneous rocks of all ages, from palæozoic up to recent times (diabase, basalt, andesite, &c.)

Its weathering also agrees with that of hornblende. The aluminous varieties containing usually some lime give rise to calcareous and ferruginous carbonates, from which the fine interstices and cavities of the surrounding rock are eventually filled with threads and kernels of calcite and strings of hydrous ferric oxide. In basalt and dolerite, for example, the weathered surface acquires often a rich yellow colour from the oxidation and hydration of the ferrous oxide.

Diallage. Monoclinic, but usually with undefined contours, distinguished by a very perfect cleavage in the direction of the orthopinakoid, feeble pleochroism, a finely fibrous structure, and a pearly to metalloidal lustre on cleavage faces. H. 4. Gr. 3·23—3·34. Essentially similar in chemical composition to augite, of which it may be only a variety, containing silica 50—53, magnesia 15—17, alumina 1—4, lime 15—22, ferrous oxide (and usually also manganous oxide) 5—13 per cent. A constituent of gabbro.

Enstatite. Orthorhombic, with cleavage parallel to faces of prism; colourless, light grey, yellowish, greenish, or brown, with pearly lustre on the cleaved surfaces. H. 5·5. Gr. 3·10—3·29. Under the microscope it presents irregularly defined forms with usually a finely fibrous structure; pleochroism feeble or absent. A meta-silicate of magnesium (with silica 60, magnesia 40 per cent., but commonly with a little ferrous oxide and alumina). Occurs in lherzolite, serpentine, and other olivine rocks. Bastite is probably a hydrated enstatite.

Bronzite. Orthorhombic, with very perfect brachydiagonal cleavage; brown, green, and yellow with a characteristic pearly metalloidal lustre and a finely fibrous surface on cleavage planes. H. 4—5. Gr. 3—3·5. Under the microscope shows weak pleochroism. Like enstatite, is found to occur as a constituent of rocks only in irregularly defined crystalline grains, and not in definite crystals; both minerals usually present the finely fibrous texture above referred to, the structure being on the whole straighter in enstatite and more undulating in bronzite.—An isomorphous mixture of silicates of magnesium and of iron, with silica 55—57 per cent., magnesia 25—36, protoxide of iron 7 to 10, and frequently a little alumina and manganese. It occurs under similar conditions to enstatite and is found also in some basalts and even in meteorites. Bronzite and enstatite weather into dull green serpentinous products.

Hyperstheue, a massive and granular mineral, isomorphous with enstatite, having a perfect brachydiagonal cleavage, black to dark green or brown colour, and metalloidal coppery lustre on the leading cleavage planes. H. 6. Gr. 3·3—3·4. Chemically like bronzite, but with rather less magnesia (11—26 per cent.) and more iron (10 to 34 per cent.). Under the microscope distinctly pleochroic, with crowded lamellæ of dark microliths, partly of magnetite. Occurs in hypersthenite and associated with other magnesian minerals among the crystalline schists.

Omphacite, a granular variety of pyroxene, grass green in colour, and commonly associated with red garnet in the rock known as eclogite.

Smaragdite, a grass green lamellar aggregate of pyroxene and hornblende, or sometimes rather of hornblende only. Occurs in gabbro and eclogite, always in crystalline indefinite pieces, never in regularly formed crystals.

Uralite, a mineral having the crystalline form of augite (pyroxene) and the internal cleavage and structure of hornblende (amphibole). It is regarded as a product of the gradual alteration of augite into hornblende. A marked finely fibrous texture and silky lustre distinguishes the cleavage planes. Under the microscope a still unchanged kernel of augite may in some specimens be observed in the centre of a crystal surrounded by strongly pleochroic hornblende, with its characteristic cleavage.

Olivine (Peridot). Orthorhombic, in dispersed crystals or granules of a pale yellowish, olive-green, or bottle-glass green tint, transparent when fresh, but apt to become dull, dark, and opaque by weathering.

FIG. 6.—STAGES IN THE ALTERATION OF OLIVINE. A, THE NEARLY FRESH CRYSTAL; B, THE ALTERATION HALF COMPLETED; C, THE CRYSTAL WHOLLY SERPENTINIZED.

H. 6·5—7. Gr. 3·2—3·5. Composed of an isomorphous mixture of the normal magnesium silicate, $Mg_2 Si O_4$, with the ferrous silicate, $Fe_2 Si O_4$ = silica 40·98, magnesia 49·18; protoxide of iron 9·84. Under the microscope with polarized light, olivine gives, when fresh, bright colours, specially red and green, but is not perceptibly pleochroic. Its orthorhombic outlines can sometimes be readily observed, but it often occurs in irregularly shaped granules or

in broken crystals. It is liable to be traversed by fine fissures, which are particularly developed transverse to the vertical axis. It is more liable to alteration than almost any other mineral constituent of rocks. The change begins on the outer surface and extends inwards and specially along the fissures, until the whole is converted either into a green granular or fibrous substance, which is probably in most cases serpentine (Fig. 6), or into a reddish yellow amorphous mass (limonite).

Olivine forms an essential ingredient of basalt, likewise the main part of various, so-called olivine-rocks or Peridotites (as lherzolite and pikrite), and occurs in many gabbros.

Leucite. Tetragonal, in isolated icositetrahedrons of a greyish-white colour, semi-transparent. H. 5·5. Gr. 2·45—2·50; infusible and unchanged before the blowpipe. Composition—silica 54·97, alumina 23·50, potash 21·53. Under the microscope sections of this mineral are usually eight-sided, and very commonly contain enclosures of magnetite, &c., conforming in arrangement to the external form of the crystal. Leucite is a markedly volcanic mineral, occurring as an abundant constituent of many ancient and modern Italian lavas, and in some varieties of basalt.

Nepheline. Hexagonal, in small prisms or in crystalline and granular aggregates, usually clear and colourless with vitreous lustre. H. 5·5—6. Gr. 2·58—2·64. Composition—silica 41·24, alumina 35·26, soda 17·04, potash 6·46. Presents under the microscope various six-sided and even four-sided forms, according to the angles at which the prisms are cut.[1] Essentially a volcanic mineral, being an abundant constituent of phonolite, of some Vesuvian lavas, and of some forms of basalt.

Under the name of *Elæolite* are comprised the greenish or reddish, dull, greasy-lustred compact or massive varieties of nepheline which occur in some syenites and other ancient crystalline rocks.

Hauyne. Isometric, but usually in solitary crystalline grains of a sky-blue to bluish-green colour; this tint, probably due, as in lapis-lazuli, to a mixture of sulphur and sodium, is discharged by heating. H. 5—5·5. Gr. 2·4—2·5. Composition—silica 34·06, alumina 27·64, soda 11·79, potash 4·96, lime 10·60, sulphuric acid 11·25. Occurs abundantly in Italian lavas, in basalt of the Eifel and elsewhere.

Nosean. Isometric, in solitary rhombic dodecahedrons, grey, greenish-blue to black, often with a dull opaque border. H. 5·5. Gr. 2·28—2·40. Composition—silica 36·13, alumina 30·95, soda 24·89, sulphuric acid 8·03, with a little chlorine, supposed to be due to a slight intermixture of the mineral sodalite. Under the microscope, one of the most readily recognized minerals, showing a hexagonal or quadrangular figure with a characteristic broad dark border corresponding to the external contour of the crystal, and where weathering has not proceeded too far, enclosing a clear

[1] On microscopic distinction between nepheline and apatite, see Fouqué et Michel-Lévy, *op. cit.* p. 276.

colourless centre. Occurs in minute forms in most phonolites, also in large crystals in some sanidine volcanic rocks.

Both hauyne and nosean are volcanic minerals associated with the lavas of more recent geological periods.

Epidote. Monoclinic, in elongated prisms, also granular, fibrous, and massive, usually of a peculiar and characteristic yellowish-green colour. H. 6—7. Gr. 3·32—3·50. Composition—silica 36—40, alumina 18—29, ferric oxide 7—17, lime 21—25. Under the microscope, appears as a constituent of rocks in yellow needles and threads, often divergent; with distinct pleochroism and remarkably bright limpid yellow and orange polarization tints. Occurs in many crystalline, chiefly hornblende-bearing, rocks, probably as a result of the alteration of the hornblende; largely distributed in certain schists and quartzites, sometimes associated with beds of magnetite and hæmatite.

Vesuvianite (Idocrase). Tetragonal, in short often vertically striated prisms or compact aggregations, occurring in druses rather than in the body of a rock; yellowish, greenish to black. H. 6·5. Gr. 3·34—3·44. Composition—Silica 37—39, alumina 13—16, ferric oxide 4—9, lime 33—37, alkalies less than 1 per cent., frequently with a little magnesia, ferrous oxide, and 2—3 per cent. of water. Occurs in ejected blocks of altered limestone at Somma, also among crystalline limestones and schists.

Andalusite. Orthorhombic, often in large long prisms as well as in compact massive aggregates; white, grey, brown, red. H. 7·5. Gr. 3·05—3·35. Composition—silica 36·90, alumina 63·10. Found in crystalline schists. The variety *Chiastolite*, which occurs abundantly scattered through some dark clay-slates, is distinguished by the regular manner in which the dark substance of the surrounding matrix has been enclosed within the macles, giving a cross-like transverse section. These crystals have been developed in the rock after its formation, and are regarded as proofs of metamorphism. (Book IV. Part VIII.)

Dichroite (Cordierite, Iolite). Orthorhombic, usually in indistinct short prisms and crystalline grains, bluish in colour, with greasy to vitreous lustre and fracture like that of quartz. H. 7—7·5. Gr. 2·56—2·67. Composition—silica 49—50, alumina 32—39, ferric oxide 5—9, magnesia 10—12, usually with a little manganous oxide, lime and water. Occurs in gneiss, sometimes in large amount (cordierite-gneiss), occasionally as an accessory ingredient in some granites; also in talc-schist. Apt to be confounded with quartz, but usually gives marked dichroism with one Nicol prism, and pale grey-blue tints with the two prisms. Undergoes numerous alterations, having been found changed into pinite, chlorophyllite, mica, &c.

Garnet. Isometric, usually in rhombic dodecahedrons and icositetrahedrons, also granular and massive; mostly some shade of red, but also green, yellow, brown, and black; vitreous to greasy lustre, pellucid to nearly opaque. Composition various, but essentially a

monosilicate of peroxide and protoxide bases, these being chiefly alumina, iron, chromium and manganese; the proportion of silica ranging between 36 and 41 per cent. Under the microscope, garnet as a constituent of rocks presents three-sided, four-sided, six-sided, eight-sided (or even rounded) figures, according to the angle at which the individual crystals are cut; usually clear, but full of flaws and often of cavities; passive in polarized light. The common red and brown varieties occur as essential constituents of eclogite, garnet rock; and as abundant accessories in mica-schist, gneiss, granite, &c.

Tourmaline (Schorl). Rhombohedral, frequently in prisms and needles, also massive, compact, and columnar; generally black, with vitreous lustre. H. 7—7·5. Gr. 2·94—3·3. Composition remarkably complex and varied, including silica (36—40 per cent.), alumina (29—40), magnesia (0·5—12), boric acid (3—9), with smaller proportions of phosphoric acid, ferrous oxide, manganous oxide, lime, potash, soda, lithia, fluorine and water; pleochroism strongly marked. With quartz forms tourmaline-rock associated with some granites; occurs also diffused through many granites, gneisses, schists, crystalline limestones, and dolomites.

Zircon. Tetragonal, in prisms, pyramids, or rounded crystalline grains; colourless to red, yellow, or brown; transparent to opaque; vitreous lustre. H. 7·5. Gr. 4·4—4·7. Composition—one molecule of silica and one of zirconia ($=Si\,O_2$ 33·2, $Zr\,O_2$ 66·8) with a little oxide of iron as colouring matter. In polarized light gives bright colours between crossed Nicols. Occurs as a chief ingredient in the zircon syenite of Southern Norway; sparingly in other syenites, granites, gneisses, crystalline limestones and schists, in eclogite, as clear red grains in some basalts, and also in ejected volcanic blocks.

Titanite. Monoclinic in thin wedge-shaped crystals (sphene); yellow, green or brown to black; vitreous to adamantine lustre. H. 5—5·5. Gr. 3·4—3·6. Composition—silica 30·61, titanic acid 40·82, lime 28·57. Between crossed Nicols gives dark yellowish-brown tints. Dispersed in small crystals in many syenites, also in granite, gneiss, and in some volcanic rocks (basalt, trachyte, phonolite).

Zeolites. Under this name is included a characteristic family of minerals, which have resulted from the alteration and particularly from the hydration of other minerals, especially of felspars. They are thus secondary products, and not original constituents of rocks. They are marked by the following general characters: usually colourless, transparent, or translucent, with a vitreous lustre which often becomes pearly on cleavage faces; H. 4—5·5; Gr. 1·9—2·5; occur in cavities of rocks, both as prominent amygdules and veins, and in minute interstices only perceptible by the microscope. In these minute forms they very commonly present a finely fibrous divergent structure. They are hydrous aluminous silicates with variable proportions of lime, potash, soda, or baryta. A relation may often be traced between the containing rock and its enclosed zeolites. Thus among the basalts of the inner Hebrides the dirty green decomposed

amygdaloidal sheets are the chief repositories of zeolites, while the firm, compact, columnar beds are comparatively free from these alteration products.[1]

Kaolin, pure clay or hydrous silicate of alumina (silica 46·3, alumina 39·8, water 13·9) resulting from the alteration of potash and soda felspars exposed to atmospheric influences, is white, but may be variously coloured by impurities. Ordinary clay is similarly formed, but contains iron, lime, and other ingredients, among which the débris of the undecomposed constituents of the original rock forms usually a marked proportion.

Talc, usually in foliated, inelastic scales, scaly aggregates or rosettes with very perfect basal cleavage; white or greenish with pearly lustre. H. 1—1·5. Gr. 2·69—2·80. Composition—silica 63·5, magnesia 31·7, water 4·8; not soluble in acids. Occurs as an essential constituent of talc-schist, and as an alteration product replacing mica, hornblende, augite, olivine, diallage, and other minerals in crystalline rocks. Under the microscope appears in small scales, which, cut transverse to basal cleavage, show ragged edges and an internal fibrous structure, the fibres not being parallel as in muscovite; is not pleochroic; polarization colours, bright yellow and red.

Chlorite includes several varieties or species occurring in small green hexagonal tables or scaly vermicular or earthy aggregates. H. 1—1·5. Gr. 2·78—2·95. Composition variable—silica 25—28, alumina 19—23, ferrous oxide 15—29, magnesia 13—25, water 9—12. Under the microscope appears markedly radiated in thin plates or spherulites with internal confused radiating fibrous structure. An essential ingredient of chlorite-schist. Occurs abundantly as an alteration product (of hornblende, &c.) in fine filaments, incrustations, and layers in many crystalline rocks.

Serpentine, not crystallized, or at least only fibrous, granular, and compact, breaking with a dull conchoidal sometimes smooth splintery fracture. H. 3—4. Gr. 2·5—3·7. Dirty-greenish, yellowish reddish or brownish colours; often streaked and veined. Consists of a hydrous magnesian silicate, viz., silica 43·48, magnesia 43·48, water 13·04, with a little ferrous silicate. Under the microscope it presents in very thin slices a pale leek-green or bluish-green base, showing aggregate polarization. Through this base runs a network of dark opaque threads and veinings. Sometimes among these veinings, or through the network of green serpentinous matter in the base, the form of original olivine crystals may be traced. There can be little doubt that serpentine is, in most cases at least, a product of the alteration of pre-existing minerals, and especially of olivine. It occurs in nests, grains, threads, and veins in rocks which once contained olivine,[2] (p. 77), also massive as a rock, in which it has replaced olivine, enstatite or some other magnesian bisilicate. This massive condition is described at p. 151.

[1] See Sullivan in Jukes' *Manual of Geology*, 3rd edit. p. 85.
[2] See Tschermak, *Wien. Akad.* lvi. 1867.

Delessite, in kernels or incrustations, with a finely fibrous or delicately scaly internal structure; olive to blackish-green. H. 2—2·5. Gr. 2·89. Composition—silica 31·07, alumina 15·47, ferric oxide 17·54, ferrous oxide 4·07, magnesia 19·14, lime 0·46, water 11·55, the iron being sometimes entirely as protoxide. Gives off water in matrass and becomes brown; easily decomposed in acids with residue of silica. Occurs abundantly as a decomposition product of augitic rocks, coating or filling amygdaloidal cavities or narrow filamentous veins.

Glauconite. A soft greenish granular mineral of variable composition, found in many stratified formations, particularly among sandstones and limestones, where it envelopes grains of sand, or fills and coats foraminifera and other organisms, giving a general green tint to the rock. Silica 47—58, alumina 3—10, ferric oxide 0—22, ferrous oxide 3—22, magnesia 0—6, lime 0—2·5, potash 4·5—9, water 5·5—14·7. It is at present being formed on the sea-floor off the coasts of Georgia and South Carolina, where Pourtales found it filling the chambers of recent polythalamia.

Carbonates. This family of minerals furnishes only four which enter largely into the formation of rocks, viz., Carbonate of Calcium in its two forms, Calcite and Aragonite, Carbonate of Magnesium (and Calcium) in Dolomite, and Carbonate of Iron in Siderite.

Calcite. Rhombohedral, but with great diversity of crystalline forms, most frequently in rhombohedra, as in the form called "nail-head spar," in scalenohedra, as in "dog-tooth spar," or in hexagonal prisms; also fibrous, granular, or pulverulent; white, but often stained with impurities; lustre vitreous to dull. H. 3. Gr. 2·6—2·8. Cleavage rhombohedral, very perfect, giving angles of 105° 5′ and 74° 5′. Composition—calcic carbonate or carbonate of lime, $Ca\ Co_3$, but frequently with some ferrous or manganous oxide, &c., and often with enclosures of other minerals. Effervesces easily with acids. Occurs as (1) an original constituent of many aqueous rocks (limestone, calcareous shale, &c.), either as a result of chemical deposition from water (calc-sinter, stalactites, &c.), or as a secretion by plants or animals[1]; or (2) as a secondary product resulting from weathering, when it is found filling or lining cavities, or diffused through the capillary interstices of minerals and rocks. It probably never occurs as an original ingredient in the massive crystalline rocks, such as granite, felsite, and lavas. Under the microscope, calcite is readily distinguishable by its intersecting cleavage lines, by a frequent twin lamellation (sometimes giving interference colours), strong double refraction, weak or inappreciable pleochroism, and characteristic iridescent polarization tints of grey, rose and blue.

From the readiness with which water absorbs carbon dioxide, from

[1] Mr. Sorby has recently investigated the condition in which the calcareous matter of the harder parts of invertebrates exists. He finds that in foraminifera, echinoderms, brachiopods, crustacea, and some lamellibranchs and gasteropods, it occurs as calcite; that in nautilus, sepia, most gasteropods, many lamellibranchs, &c., it is aragonite; that in not a few cases the two forms occur together, or that the carbonate of lime is hardened by an admixture of phosphate. *Quart. Journ. Geol. Soc.* 1879. Address, p. 61.

the increased solvent power which it thereby acquires, and from the abundance of calcium in various forms among minerals and rocks, it is natural that calcite should occur abundantly as a pseudomorph replacing other minerals. Thus it has been observed taking the place of a number of silicates, as orthoclase, oligoclase, garnet, augite, and several zeolites; of the sulphates, anhydrite, gypsum, barytes, and celestine; of the carbonates, aragonite, dolomite, cerussite; of the fluoride, fluor-spar; and of the sulphide, galena. Moreover, in many massive crystalline rocks (diorite, dolerite, &c.), which have been long exposed to atmospheric influence, this mineral may be recognised by the brisk effervescence produced by a drop of acid, and in microscopic sections appears filling the crevices, or sending minute veins among the decayed mineral constituents. Calcite is likewise the great petrifying medium; the vast majority of the animal remains found in the rocky crust of the globe have been replaced by calcite, sometimes with a complete preservation of internal organic structure, sometimes with a total substitution of crystalline material for that structure, the mere outer form of the organism alone surviving.

Aragonite. Orthorhombic, also globular, columnar, fibrous, stalactitic, and encrusting. H. 3·5—4. Gr. 2·9—3. Composition same as calcite. The cause of the crystallization of calcium carbonate in the form of aragonite rather than calcite is still uncertain. Aragonite differs from calcite in being harder and heavier. It is much less abundant than the latter mineral, which is the more stable form of this carbonate. It occurs with beds of gypsum, also in mineral veins, in strings running through basalt and other igneous rocks, and in the shells of many mollusca. It is thus always a deposit from water, sometimes from mineral springs, sometimes as a result of the internal alteration of rocks, and sometimes through the action of living organisms. Being more easily soluble than calcite, it has no doubt in many cases disappeared from limestones originally formed mainly of aragonite shells, and has been replaced by the more durable calcite, with a consequent destruction of the traces of organic origin. Hence what are now thoroughly crystalline limestones may have been formed by a slow alteration of such shelly deposits.

Dolomite (Bitter-spar). Rhombohedral and isomorphous with calcite, the crystals usually visible only in open spaces of rocks; but most frequently granular and amorphous. H. 3·5—4·5. Gr. 2·85—2·95. Composition—calcium carbonate 54·35, magnesium carbonate 45·65, but these proportions are not constant, and the mineral is liable also to contain some ferrous or manganous carbonate. Only slowly acted on with little or no effervescence by cold acids, but when powdered soluble in warm acid. Occurs (1) as an original formation in massive beds (magnesian limestone) belonging to many different geological formations; (2) as a product of alteration, especially of ordinary limestone or of aragonite (p. 304).

Siderite (Brown Ironstone Spathic Iron, Chalybite). Rhombohedral, with curved cleavage faces, also common in finely fibrous

or coarse granular amorphous aggregates. H. 3·5—4·5. Gr. 3·7—3·9. Composition—ferrous carbonate or carbonate of the protoxide of iron (=ferrous oxide 62·07, carbon dioxide 37·93), but seldom with the theoretically pure composition; usually with an intermixture of other carbonates (especially of manganese, magnesium, and calcium), and in the coarse varieties with clay and many other impurities. Occurs crystallized in association with metallic ores, also in beds and veins of many crystalline rocks, particularly with limestones; the compact argillaceous varieties (clay ironstone) are found in abundant nodules and beds in the shales of Carboniferous and other formations where they have been deposited from solution in water in presence of decaying organic matter (see pp. 115, 175).

Sulphates. Among the sulphates of the mineral kingdom, only three deserve notice here as important compounds in the constitution of rocks—viz., calcium sulphate or sulphate of lime in its two forms, Anhydrite and Gypsum, and barium sulphate or sulphate of baryta in Barytes.

Anhydrite. Orthorhombic; fibrous, lamellar, granular. H. 3—3·5. Gr. 2·8—3. Composition—anhydrous calcium sulphate (= sulphuric acid 58·82, lime 41·18). Occurs more especially in association with beds of gypsum and rock-salt.

Gypsum. Monoclinic; granular, foliated, fibrous, massive. H. 1·5—2. Gr. 2·2—2·4. Composition—hydrous calcium sulphate (= sulphuric acid 46·51, lime 32·54, water 20·95). Abundant as an original aqueous deposit in many sedimentary formations. (See p. 115.)

Barytes (Heavy Spar). Orthorhombic; also crested, fibrous, coarsely laminated. H. 3—3·5. Gr. 4·3—4·7. Composition—barium sulphate (=baryta 65·7, sulphuric acid 34·3). Frequent in veins traversing rocks of many different kinds, and especially associated with metallic ores as one of their characteristic vein-stones.

Phosphates. The phosphates which occur most conspicuously as constituents or accessory ingredients of rocks are the tricalcic phosphate or Apatite, and triferrous phosphate or Vivianite.

Apatite. Hexagonal in six-sided prisms; colourless, grey, green, yellow, and red, usually opaque except in minute crystals; also massive (phosphorite). H. 5. Gr. 3·16—3·22. Composition—Neutral phosphate of calcium, with fluoride or chloride of calcium, or both. Occurs in many igneous rocks (granites, basalts, &c.), in minute non-pleochroic needles giving faint polarization tints; also as massive beds associated with metamorphic rocks.

Vivianite (Blue iron-earth). Monoclinic, also often globular and earthy. H. 1·5—2. Gr. 2·6—2·7. Usually bluish or bluish-green. Composition—hydrous triferrous phosphate (= protoxide of iron 43·03, phosphoric acid 28·29, water 27·95, but the iron frequently more or less altered into peroxide). Occurs crystallized in metalliferous veins; the earthy variety is not infrequent in peat-mosses where animal matter has decayed, and is sometimes to be observed coating fossil fishes as a fine layer like the bloom of a plum.

Fluorides. The element fluorine, though widely diffused in

nature, occurs only in comparatively small quantity. Its most abundant compound is with Calcium as the common mineral Fluorite.

Fluorite (Fluor-spar). Isometric, usually in cubes; also massive; colour ranging most commonly through many shades of yellow, blue, and green. H. 4. Gr. 3·1—3·2. Composition—fluoride of calcium (= fluorine 48·72, calcium 51·28). Occurs generally in veins, especially in association with metallic ores.

CHLORIDES. There is only one chloride of importance as a constituent of rocks—sodium chloride or common salt. As it occurs chiefly in beds as a rock-formation, it is described among the rocks at p. 111.

SULPHIDES. Sulphur is found united with metals in the form of sulphides, many of which form common minerals. The sulphides of lead, silver, copper, zinc, antimony, &c., are of great commercial importance. The sulphide of iron, however, is the only one which merits consideration here as a rock-forming substance. It occurs in two forms, Pyrite and Marcasite.

Pyrite (Eisenkies, Schwefelkies). Isometric, abundant in cubes; also globular, with internal radiating fibrous structure, and amorphous. Colour, pale brass yellow, with splendent metallic lustre. H. 6—6·5. Gr. 4·9—5·2. Composition—iron disulphide, $Fe\,S_2$ (= sulphur 53·33, iron 46·67), but usually with traces of other metals. Occurs disseminated through almost all kinds of rocks, often in great abundance, as among dolerites and diabases; also frequent in veins or in beds. Iron disulphide is formed at the present day by some thermal springs, and has been developed in many rocks as a result of the action of infiltrating water in presence of decomposing organic matter and iron salts. In microscopic sections of rocks, pyrite appears in small cubical, perfectly opaque crystals, which with reflected light show the characteristic brassy lustre of the mineral, and cannot thus be mistaken for the isometric magnetite, of which the square sections exhibit a characteristic blue-black colour. Pyrite when free from marcasite yields but slowly to weathering. Hence its cubical crystals may be seen projecting still fresh from slates which have been exposed to the atmosphere for several generations.

Marcasite (Hepatic pyrites). Orthorhombic, but frequently also in fibrous, rounded or encrusting masses, or in amorphous aggregates. Colour paler than pyrite. H. 6—6·5. Gr. 4·65—4·88. Composition same as pyrite. Occurs abundantly among sedimentary formations, sometimes diffused in minute particles, sometimes segregated in layers, or replacing the substance of fossil plants or animals; also in veins through crystalline rocks. This form of the sulphide is especially characteristic of stratified fossiliferous rocks, and more particularly of those of Secondary and Tertiary date. It is extremely liable to decomposition. Hence exposure for even a short time to the air causes it to become brown, free sulphuric acid is produced, which attacks the surrounding minerals, sometimes at once forming sulphates, at other times decomposing aluminous silicates and dissolving them in con-

siderable quantity. Dr. Sullivan mentions that the water annually pumped from one mine in Ireland carries up to the surface more than a hundred tons of dissolved silicate of alumina.[1] Iron disulphide is thus an important agent in effecting the internal decomposition of rocks. It also plays a large part as a petrifying medium, replacing the organic matter of plants and animals, and leaving casts of their forms, often with bright metallic lustre. Such casts when exposed to the air decompose.

§ III.—*General Macroscopic Characters of Rocks.*[2]

Rocks considered as mineral substances are distinguished from each other by certain external characters, such as size, form, and arrangement of component particles. These characters, readily perceptible to the naked eye, and in the great majority of cases observable in hand specimens, are termed *macroscopic*, to distinguish them from the more minute features of structure which, being only visible or satisfactorily observable when greatly magnified, are known as *microscopic*. The latter features are described at p. 94. The larger (geotectonic) aspects of rock-structure, which can only be properly examined in the field and belong to the general architecture of the earth's crust, are treated of in Book IV.

In the discrimination of rocks, it is not enough to specify their component minerals, for the same minerals may constitute very distinct varieties of rock. For example, quartz and mica form the massive crystalline rock, greisen, the foliated crystalline rock, mica-schist, and the sedimentary rock, micaceous sandstone. Chalk, encrinal limestone, stalagmite, statuary marble are all composed of calcite. It is needful to take note of the general structure, texture, state of aggregation, colour, and other characters of the several masses.

1. **Structure.**—The different kinds of macroscopic rock-structure are denoted either by ordinary descriptive adjectives, or by terms derived from rocks in which the special structures are characteristically developed, such as granitoid, brecciated, shaly. The following are the more important varieties.

Crystalline, consisting wholly or chiefly of crystalline particles or crystals. Where the individual elements of the rocks are of large size, the structure is *coarse-crystalline*, as in many granites. When the particles are readily visible to the naked

[1] Jukes' *Manual of Geology*, 3rd edit. p. 65.

[2] The following general text-books on rocks may be referred to: Macculloch, *A Geological Classification of Rocks*, &c., London, 1821. B. von Cotta, *Rocks Classified and Described*, translated by Lawrence, London, 1866. Zirkel, *Lehrbuch der Petrographie*, two vols. Bonn, 1866. Senft, *Classification der Felsarten*, Breslau, 1857; *Die Krystallinischen Felsgemengtheile*, Berlin, 1868. Bischof, *Chemical Geology*, translated for Cavendish Society, 1854–59, and supplement, Bonn, 1871. Roth, *Allgemeine und Chemische Geologie*, Berlin, 1879. Other works in which the microscopical characters are more specially treated of, are enumerated on p. 94.

eye, and are tolerably uniform in size, as in most granites, the rock is said to be granular-crystalline. Successive stages in the diminution of the size of the particles are denoted by the terms *fine-crystalline*, *micro-crystalline*, and *crypto-crystalline*, the last being applied when the individual crystalline particles can no longer be detected with the naked eye. Such fine-grained rocks may also be called *compact*, though this term is likewise applicable to the more close-grained varieties of the fragmental series.

Many crystalline rocks consist not only of crystals, but of a magma or paste, in which the crystalline particles are seen by the naked eye to be embedded. It is of course impossible, except from analogy, to determine macroscopically what may be the nature of this magma. It may be entirely composed of minute crystals, or may consist of various crystallitic products of devitrification. Its intimate structure can only be ascertained with the microscope. But its existence is often strikingly manifest even to the unassisted eye, for in what are termed "porphyries" it forms the main part of their mass. The term "*ground-mass*" has been employed by Zirkel and others to denote this macroscopic matrix. Microscopic examination shows that a ground-mass may consist of minute crystals, or crystallites, or granules and filaments, or glass, or combinations of these in various proportions. (See p. 100.)

Vitreous or glassy, having a structure like that of artificial glass, as in obsidian. Most vitreous rocks present even to the naked eye dispersed grains, crystals, or other enclosures. Under the microscope they are found to be often crowded with minute crystals and imperfect or incipient crystalline forms (p. 99). Resinous is the term applied to vitreous rocks having the lustre of pitchstone and others which are still less vitreous. Devitrification is the conversion of the vitreous into a crystalline or lithoid structure (p. 100).

Horny, flinty, having a compact, homogeneous dull texture, like that of horn or flint, especially exemplified by colloid silica, as in calcedony, jasper, flint.

Clastic, fragmental, composed of detritus. Rocks possessing this character have in the great majority of cases been formed in water, and their component fragments are usually more or less rounded or water-worn. Different names are applied, according to the form or size of the fragments. *Brecciated*, composed, like a breccia, of angular fragments, which may be of any degree of coarseness. *Agglomerated*, consisting of large, roughly rounded and tumultuously grouped blocks, as in the agglomerate filling old volcanic funnels. *Conglomerated* (*Conglomeratic*), made up of well-rounded blocks or pebbles; rocks having this character have been formed by and deposited in water. *Pebbly*, containing dispersed water-worn pebbles, as in many coarse sandstones, which thus by degrees pass into conglomerates. *Psammitic*, or sandstone-like, composed of rounded grains, as in ordinary sandstone: when the grains are larger (often sharp and somewhat angular) the rock is *gritty*, or a grit.

Muddy (*pelitic*), having a texture like that of dried mud. *Cryptoclastic* or *compact*, where the grains are too minute to reveal to the naked eye the truly fragmental character of the rock, as in fine mudstones and other argillaceous deposits.

Granular, composed of worn grains or of irregular crystalline particles, as in dolerite, granite, sandstone and marble. This texture may become so fine as to pass insensibly into compact. The crypto-crystalline portions of some igneous rocks, where the component ingredients cannot be determined except with the microscope, are sometimes called *aphanitic*.

Massive, unstratified, having no arrangement in definite layers or strata. Lava, granite, and generally all crystalline rocks which have been erupted to the surface, or have solidified below from a state of fusion (or plasticity), are Massive rocks.

Stratified, bedded, composed of layers or beds lying parallel to each other, as in shale, sandstone, limestone, and other rocks which have been deposited in water. *Laminated*, consisting of fine leaf-like strata or laminæ; this structure being characteristically exhibited in shales, is sometimes also called *shaly*.

Foliated, consisting of minerals that have crystallized in approximately parallel lenticular and usually wavy layers or folia. Rocks of this kind commonly contain layers of mica, or of some equivalent readily cleavable mineral, the cleavage planes of which coincide generally with the planes of foliation. Gneiss, mica-schist and talc-schist are characteristic examples. So distinctive, indeed, is this structure in schists, that it is often spoken of as *schistose*. In gneiss it attains its most massive form; in chlorite-schist and some other schists it becomes so fine as to pass into a kind of minutely scaly texture, often only perceptible with the microscope, the rock having on the whole a massive structure.

Fibrous, consisting of one or more minerals composed of distinct fibres. Sometimes the fibres are remarkably regular and parallel, as in fibrous gypsum, and veins of fibrous aragonite or calcite (satin-spar); in other instances, they are more tufted and irregular, as in asbestus and actinolite-schist.

Streaked, having some or all of the component minerals arranged in streaky lines, either parallel or convergent, and often undulating. This structure, conspicuously shown by the lines of flow in vitreous rocks like obsidian, is less marked in such crystalline rocks as diorite and dolerite. It can be seen on a minute scale, however, in many crystalline masses when examined with the microscope. (See Fluxion-structure, p. 104.)

Cavernous (porous), containing irregular cavities due, in most cases, to the abstraction of some of the minerals; but occasionally, as in some limestones (sinters), dolomites and lavas, forming part of the original structure of the rock.

Cellular.—Many lavas, ancient and modern, have been saturated with steam at the time of their eruption, and in consequence of the segregation and expansion of this imprisoned vapour,

have had spherical cavities developed in their mass. When this cellular structure is marked by comparatively few and small holes, it may be called *vesicular;* where the rock consists partly of a roughly cellular, and partly of a more compact substance intermingled, as in the slag of an iron furnace, it is said to be *slaggy;* portions where the cells occupy about as much space as the solid part, and vary much in size and shape, are called *scoriaceous*, this being the character of the rough clinker-like scoriæ of a recent lava stream; when the cells are so much more numerous than the solid part, that the stone would almost or quite float on water, the structure is called *pumiceous*, the term *pumice* being the name given to the froth-like part of obsidian. As the cellular structure is necessarily developed while the rock is still liquid, or at least viscid, and as while in this condition the mass is often still moving away from its point of emission, the cells are not infrequently elongated in the direction of movement. Subsequently water infiltrating through the rock, deposits various mineral substances (calcite, quartz, calcedony, zeolites, &c.) from solution, so that the flattened and elongated almond-shaped cells are eventually filled up. A rock which has undergone this change is said to be *amygdaloidal*, and the almond-like kernels are known as *amygdules*.

Concretionary, containing or consisting of mineral matter which has been collected, either from the surrounding rock or from without, round some centre, so as to form a nodule or irregularly shaped lump. This aggregation of material is of frequent occurrence among water-formed rocks, where it may be often observed to have taken place round some organic centre, such as leaves, cones, shells, fish remains, or other relics of plants or animals. (Book IV. Part I.) Among the most frequent minerals found in concretionary forms as constituents of rocks are calcite, siderite, pyrite, marcasite, and various forms of silica. In a true concretion the material at the centre has been deposited first, and has increased by additions from without, either during the formation of the enclosing rock, or by subsequent concentration and aggregation. Where, on the other hand, cavities and fissures have been filled up by the deposition of materials on their walls, and gradual growth inward, the result is known as a secretion. Amygdules and the successive coatings of mineral veins are examples of the latter process.

Spherulitic, composed of, or containing small globules or spherules which may be colloid and isotropic or more or less distinctly crystalline, particularly with an internal fibrous divergent structure. This structure occurs in vitreous rocks, where it is one of the stages of devitrification in obsidian, pitchstone, &c. (see p. 141).

Perlitic, having the structure of the rock termed perlite, which is distinguished by being traversed by minute rectilinear fissures, between which the substance of the mass has assumed a finely globular character, not unlike the spheroidal structure seen in weathered basalt (Fig. 22).

Granitoid, thoroughly crystalline, and consisting of crystals

approximately uniform in size, as in granite. This structure is characteristic of many eruptive rocks. Though usually distinctly recognizable by the naked eye ("macromerite" of Vogelsang[1]), it sometimes becomes very fine ("micromerite"), and may be only recognizable as thoroughly crystalline with the microscope; at other times it passes into a porphyritic or porphyroid character by the appearance of large crystals dispersed through a general ground-mass.

Porphyritic, composed of a compact or finely crystalline ground-mass, through which distinct larger crystals, generally of some felspar, are dispersed. This and the granitic structure are the two great structure-types of the eruptive rocks. By far the largest number of these rocks belong to the porphyritic type. Vogelsang has proposed to classify this type in three divisions: 1st, *Granophyre,* where the ground-mass is a microscopic crystalline mixture of the component minerals with a sparing development of an imperfectly individualized magma (see p. 103); 2nd, *Felsophyre* having usually an imperfectly individualized or felsitic magma for the ground-mass (p. 104); 3rd, *Vitrophyre,* where the ground-mass is a glassy magma. The second sub-division embraces most of the porphyries, and a very large number of eruptive rocks of all ages.[2]

Segregated.—In granite and other crystalline massive rocks, vein-like portions, coarser (or finer) in texture than the rest of the mass, may be observed. These "contemporaneous veins," as they have been called, belong to the last phase of consolidation, when segregations from the original molten or viscous magma took place along certain lines where from fracture or otherwise the individual minerals could crystallize out from the general mass. They have been sometimes termed "segregation," or "exudation" veins.

2. Composition.—Before having recourse to chemical or microscopic analysis, the geologist can often pronounce as to the general chemical or mineralogical nature of a rock. Most of the terms which he employs to express his opinion are derived from the names of minerals, and in almost all cases are self-explanatory. The following examples may suffice. Calcareous, consisting of or containing carbonate of lime. Argillaceous, consisting of or containing clay. Felspathic, having some form of felspar as a constituent. Siliceous, formed of or containing silica; usually applied to the colloid or calcedonic forms of this oxide. Quartzose, containing or consisting entirely of some form of quartz; used more particularly of the crystalline forms of silica. Carbonaceous, containing coaly matter, and hence usually associated with a dark colour. Pyritous, containing diffused disulphide of iron. Gypseous, containing layers, nodules, or scattered crystals of calcium sulphate. Saliferous, containing beds of, or impregnated with, rock salt.

As rocks are not definite chemical compounds, but mixtures of

[1] *Z. Deutsch. Geol. Ges.* xxiv. p. 534.

[2] Vogelsang, *loc. cit.* Compare the classification as *granitoid* and *trachytoid, postea,* p. 130.

different minerals in varying proportions, they exhibit many intermediate varieties. Transitions of this kind are denoted by such phrases as "granitic gneiss," that is, a gneiss in which the normal foliated structure is nearly merged into the massive structure of granite; "argillaceous limestone"—a rock in which the limestone is mixed with clay; "calcareous shale"—a fissile rock consisting of clay with a proportion of lime. It is evident that such rocks may graduate so insensibly into each other, that no sharp line can be drawn between them either in the field or in their terminology.

3. **State of Aggregation.**—The hardness or softness of a rock, in other words, its induration and friability, or the degree of aggregation of its particles, may be either original or acquired. Some rocks (sinters for example) are soft at first and harden by degrees; the general effect of exposure, however, is to loosen the cohesion of the particles of rocks. A rock which can easily be scratched with the nail is almost always much decomposed, though some chloritic and talcose schists are soft enough to be thus affected. Compact rocks which can easily be scratched with the knife, and are apparently not decomposed, may be fine grained limestones, dolomites, ironstones, mudstones, or some other simple rocks. Crystalline rocks, as a rule, cannot be scratched with the knife unless considerable force be used. They are chiefly composed of hard silicates, so that when an instance occurs where a fresh specimen can be easily scratched, it will generally be found to be a limestone (see § vii. p. 179). The ease with which a rock may be broken is the measure of its frangibility. Most rocks break most easily in one direction; attention to this point will sometimes throw light upon their internal structure.

Fracture is the surface produced when a rock is split or broken, and depends for its character upon the texture of the mass. Finely granular compact rocks are apt to break with a *splintery* fracture where wedge-shaped plates adhere by their thicker ends to, and lie parallel with, the general surface. When the rock breaks off into concave and convex rounded shell-like surfaces, the fracture is said to be *conchoidal*, as may be seen in obsidian and other vitreous rocks, and in exceedingly compact limestones. The fracture may also be *foliated*, *slaty*, or *shaly*, according to the structure of the rock. Many opaque, compact rocks are translucent on the thin edges of fracture, and afford there, with the aid of a lens, a glimpse of their internal composition. A rock is said to be *flinty*, when it is hard, close-grained, and breaks with a smooth or conchoidal fracture like flint; *friable*, when it crumbles down like dried clay or chalk; *plastic*, when like moist clay it can be worked into shapes; *pulverulent*, when it falls readily to powder; *earthy*, when it is decomposed into loam or earth; *incoherent* or *loose*, when its particles are quite separate, as in dry blown sand.

4. **Colour and Lustre.**—These characters vary so much even

in the same rock, according to the freshness of the surface examined, that they possess but a subordinate value. Nevertheless, when cautiously used, colour may be made to afford valuable indications as to the probable nature and composition of rocks. It is in this respect always desirable to compare a freshly-broken with a weathered piece of the rock.[1]

White indicates usually the absence or comparatively small amount of the heavy metallic oxides, especially iron. It may either be the original colour, as in chalk and calc-sinter, or may be developed by weathering, as in the white crust on flints and on many porphyries. *Black* may be due either to the presence of carbon (when weathering will not change it much), or to some iron-oxide (magnetite chiefly), or silicate rich in iron (as hornblende and augite). Many rocks (basalts and dolerites particularly) which look quite black on a fresh surface, become red, brown, or yellow on exposure, black being comparatively seldom a weathered colour. *Yellow*, as a dull earthy colouring matter, almost always indicates the presence of hydrated peroxide of iron. In modern volcanic districts it may be due to iron-chloride, sulphur, &c. Bright, metallic, gold-like yellow is usually that of iron-disulphide. *Brown* is the normal colour of some carbonaceous rocks (lignite), and ferruginous beds (bog-iron-ore, clay ironstone, &c.). It very generally, on weathered surfaces, points to the oxidation and hydration of minerals containing iron. *Red*, in the vast majority of cases, is due to the presence of granular anhydrous peroxide of iron. This mineral gives dark blood-red to pale flesh-red tints. As it is liable, however, to hydration, these hues are often mixed with the brown and yellow colours of limonite. *Green*, as the prevailing tint of rocks, occurs among schists, when its presence is usually due to some of the hydrous magnesian silicates (chlorite, talc, serpentine). It appears also among massive rocks, especially those of older geological formations, where hornblende, olivine, or other silicates have been altered. Among the sedimentary rocks it is principally due to ferrous silicate (as in glauconite). Carbonate of copper colours some rocks emerald or verdigris green. The mottled character so common among many stratified rocks is frequently traceable to unequal weathering, some portions of the iron being more oxidized than others; while some, on the other hand, become deoxidized from the reducing action of decaying organic matter. To the former cause may be attributed the brown and yellow hue of the exposed parts of blue clays, to the latter the circular green spots so often found among red strata.

Lustre, as an external character of rocks, does not possess the value which it has among minerals. In most rocks the granular texture prevents the appearance of any distinct lustre. A completely vitreous lustre without a granular texture, is characteristic of volcanic glass. A splendent semi-metallic lustre may often be observed upon

[1] Alterations of the colours of minerals and rocks are effected by heat and even by sunlight. See Jannettaz *Bull. Soc. Géol.* xxix. (1872) p. 300.

the foliation planes of schistose rocks and upon the laminæ of micaceous sandstones. As this silvery lustre is almost invariably due to the presence of mica, it is commonly called distinctively *micaceous*. A metallic lustre is met with sometimes in beds of anthracite; more usually its occurrence among rocks indicates the presence of metallic oxides or sulphides.

5. **Feel and Smell.**—These minor characters are occasionally useful. By the feel of a mineral or rock is meant the sensation experienced when the fingers are passed across its surface. Thus the hydrous magnesian silicates have a marked soapy or greasy feel. Some hydrous mica-schists with margarodite or an allied mica, likewise exhibit the same character. Some rocks adhere to the tongue, a quality indicative of their tendency to absorb water.

Smell.—Many rocks when freshly broken emit distinctive odours. Those containing volatile hydrocarbons give sometimes an appreciable *bituminous* odour, as is the case with some of the dolerites, which in central Scotland have been intruded through coal-seams and carbonaceous shales. Limestones have often a *fetid* odour; rocks full of decomposing sulphides are apt to give a *sulphurous* odour; those which are highly siliceous yield, on being struck, an *empyreumatic* odour. It is characteristic of argillaceous rocks to emit a strong earthy smell when breathed upon.

6. **Specific Gravity.**—This is an important character among rocks as well as among minerals. It varies from 0·6 among the hydrocarbon compounds to 3·1 among the basalts. As already stated, the average specific gravity of the rocks of the earth's crust may be taken to be about 2·5, or from that to 3·0.

The student will find this character of considerable advantage in enabling him to discriminate between rocks. He may acquire some dexterity in estimating even with the hand the probable specific gravity of substances; but he should begin by determining it with a balance. Jolly's spring balance is a simple and serviceable instrument for this purpose. It consists of an upright stem having a graduated strip of mirror let into it, in front of which hangs a long spiral wire, with rests at the bottom for weighing a substance in air and in water. For most purposes it is sufficiently accurate, and a determination can be made with it in the course of a few minutes.[1]

7. **Magnetism** is so strongly exhibited by some crystalline rocks as powerfully to affect the magnetic needle, and to vitiate observations with this instrument. It is due to the presence of magnetic iron, the existence of which may be shown by reducing a rock to powder in an agate mortar, washing carefully the triturated powder, and drying the heavy residue, from which grains of magnetite or of titaniferous magnetic iron may be extracted with a magnet.

[1] Jolly's spring balance can be obtained through any optician or mineral dealer from Berberich, of Munich, for nine florins. In the United States it is manufactured by Geo. Wade and Co., at the Hoboken Institute.

This may be done with any basalt. A freely swinging magnetic needle is of service, as by its attraction or repulsion, it affords a delicate test for the presence of even a small quantity of magnetic iron.

§ IV.—*Minute or Microscopic Characters of Rocks.*

No department of Geology has been more advanced in recent years than Lithology, and this has been mainly due to the introduction of the microscope as an instrument for investigating minute internal structure. As far back as the year 1827, a method of making thin transparent sections of fossil wood, and mounting them on glass with Canada balsam, had been devised by William Nicol of Edinburgh, and was employed by Henry Witham in an investigation of the *History of Fossil Vegetables.*[1]

It was not, however, until 1856 that Mr. H. C. Sorby, applying this method to the investigation of minerals and rocks, showed how many and important were the geological questions on which it was calculated to shed light.[2] Reference will be made in subsequent pages to the remarkable results then announced by him. To the publication of his memoir the subsequent rapid development of microscopic research among rocks may be distinctly traced. This branch of inquiry has been prosecuted more particularly in Germany, but the microscopic method of analysis is now in use in every country where attention is paid to the history of rocks.[3]

In § vii. p. 182, information is given regarding the preparation of sections of rocks for microscopical examination, the methods of procedure in the practice of this part of geological research and some of the terms employed in the following pages.

1. Microscopic Elements of Rocks.

Rocks when examined in thin sections with the microscope are found to be composed of or to contain various elements, of which the more important are, 1st, crystals, or crystalline substances; 2nd, glass; 3rd, crystallites; 4th, detritus.

[1] Small 4to, Edinburgh, 1831. This work, though dedicated to Nicol, does not distinctly recognize him as the actual inventor of the process of slicing mineral substances for microscopic investigation. All that was original in Witham's researches he owed either directly or indirectly to Nicol.

[2] *Brit. Assoc.* 1856, Sect., p. 78. *Quart. Journ. Geol. Soc.* xiv. 1858.

[3] Among the best text-books on this subject the following may be mentioned:— *Mikroskopische Beschaffenheit der Mineralien und Gesteine*, F. Zirkel, 1 vol. 1873. *Mikroskopische Physiographie der Mineralien und Gesteine*, H. Rosenbusch, 2 vols. 1873–7. *Elemente der Petrographie*, Von Lasaulx. 1875. *Minéralogie micrographique: roches éruptives françaises*, Fouqué et Michel-Lévy, 2 vols. 4to. Paris, 1879. *Microscopical Petrography*, Zirkel, being vol. vi. of the *Geol. Explor. of 40th Parallel*, Washington, 1876. The volumes for the last ten or fifteen years of the *Quarterly Journal of the Geological Society*, *Geological Magazine*, *Neues Jahrbuch für Mineralogie*, &c., *Zeitschrift der Deutschen Geologischen Gesellschaft*, *Bulletin de la Société géologique de France*, *Jahrbuch*

A. CRYSTALS OR CRYSTALLINE SUBSTANCES.—Rock-forming minerals when not amorphous may be either crystallized in their proper crystallographic forms, or crystalline, that is, possessing a crystalline internal structure, but without definite external geometrical form. The latter condition is more prevalent, seeing that minerals have usually been developed round and against each other, thus mutually hindering the assumption of determinate crystallographic contours. Other causes of imperfection are fracture by movement in the original magma of the rock and partial solution in that magma, as in the corroded quartz of quartz-porphyries and rhyolites. In some rocks, such as granite, the thoroughly crystalline character of the component ingredients is well marked, yet they seldom present the definite isolated crystals so frequently to be observed in porphyries and in many old and modern volcanic rocks. Among thoroughly crystalline rocks good crystals of the component minerals may be obtained from fissures and cavities in which there has been room for their formation. It is in the "drusy" cavities of granite, for example, that the well-defined prisms of felspar, quartz, mica, topaz, beryl and other minerals are found. Successive stages in order of appearance or development can readily be observed among the crystals of rocks. Some appear as large but frequently broken or corroded forms. These have evidently been formed first. Others are smaller but abundant, usually unbroken, and often disposed in lines. Others have been developed by subsequent alteration within the rock.[1]

A study of the internal structure of crystals throws light not merely on their own genesis, but on that of the rocks of which they consist, and is therefore well worthy of the attention of the geologist. That many apparently simple crystals are in reality compound, may not infrequently be detected by the different condition of weathering in the two opposite parts of a twin on an exposed face of rock. The internal structure of a crystal modifies the action of solvents on its exterior (*e.g.* weathered surfaces of calcite, aragonite and felspars). Crystals may occasionally be observed built up of rudimentary "microliths," as if these were the simplest forms in which the molecules of a mineral begin to appear (p. 100).

Crystalline minerals are seldom free from extraneous inclusions. These are occasionally large enough to be readily seen by the naked eye. But the microscope reveals them in many minerals in almost incredible quantity. They are, α, gas cavities; β, vesicles containing liquid; γ, globules of glass or of some lithoid substance; δ, crystals; ϵ, filaments or other indefinitely-shaped pieces, patches, or streaks of mineral matter.

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der K. K. Geologischen Reichsanstalt (*Vienna*), contain numerous papers on the microscopic structure of rocks. Rutley's *Study of Rocks*, London, 1879, is a convenient little book. The manual of Rosenbusch and the work of Fouqué and Michel-Lévy, contain a tolerably ample bibliography of the subject, to which the student is referred. The titles of some of the more important memoirs which have recently appeared will be given in footnotes.

[1] Fouqué et Michel-Lévy. *Min. Micrograph.* p. 151.

a. Gas-filled or empty cavities—are most frequently globular or elliptical, and appear to be due to the presence of gas or steam in the crystal at the time of consolidation. Zirkel estimates them at 360,000,000 in a cubic millimetre of the hauyne from Melfi.[1] In some instances the cavity has a geometric form belonging to the crystalline system of the enclosing mineral. Such a space defined by crystallographic contours is a *negative crystal.* A cavity filled with gas contains no bubble, and its margin is marked by a broad dark band. The usual gas is nitrogen, with traces of oxygen and carbon dioxide; sometimes it is entirely carbon dioxide or hydrogen and hydrocarbons.

β. Vesicles containing liquid (and gas.)—As far back as the year 1823, Brewster studied the nature of certain fluid-bearing cavities in different minerals.[2] The first observer who showed their important bearing on geological researches into the origin of crystalline rocks was Mr. Sorby, in whose paper, already cited, they occupy a prominent place. Vesicles entirely filled with liquid are distinguished by their sharply-defined and narrow black borders. Vesicular spaces containing fluid may be noticed in many artificial crystals formed from aqueous solutions (crystals of common salt show them well) and in many minerals of crystalline rocks. They are exceedingly various in form, being branching, curved, oval, or spherical, and sometimes assuming as negative crystals a geometric form, like that characteristic of the mineral in which they occur, as cubic in rock salt and hexagonal in quartz. They also vary greatly in size. Occasionally in quartz, sapphire and other minerals large cavities are readily observable with the naked eye. But they may be traced with high magnifying powers down to less than $\frac{1}{10000}$ of an inch in diameter. Their proportion in any one crystal ranges within such wide limits, that whereas in some crystals of quartz few may be observed, in others they are so minute and abundant that many millions must be contained in a cubic inch. The fluid present is usually water, frequently with saline solutions, particularly chloride of sodium or of potash, or sulphates of potash, soda, or lime. Carbon dioxide may be present in the water; sometimes the cavities are partially occupied with it in liquid form, and the two fluids, as originally observed by Brewster, may be seen in the same cavity unmingled, the carbon dioxide remaining as a freely moving globule within the carbonated water. Cubic crystals of chloride of sodium may be occasionally observed in the fluid, which must in such cases be a saturated solution of this salt (Fig. 7, lowest figure in Column A). Usually each cavity contains a small globule or bubble, sometimes stationary, sometimes movable from one side or end of the cavity to the other as the specimen is turned, sometimes slowly pulsating from side to side, or rapidly vibrating like a living organism. The cause of these movements

[1] *Mik. Beschaff.* p. 86.

[2] *Edin. Phil. Journ.* ix. p. 94. *Trans. Roy. Soc. Edin.* x. p. 1. See also W. Nicol. *Edin. New Phil. Journ.* (1828) v. p. 94.

remains still unexplained. The bubble may be made to disappear by the application of heat. Sorby pointed out that it can be imitated in artificial crystals, in which he explained its existence by diminution of volume of the liquid owing to a lowering of temperature after its enclosure. By a series of experiments he ascertained the rate of expansion of water and saline solutions up to a temperature of 200° C (392° Fahr.), and calculated from them the temperature at which the liquid in crystals would entirely fill its enclosing cavities. Thus in the nepheline of the ejected blocks of Monte Somma he found that the relative size of the vacuities was about ·28 of the fluid, and assuming the pressure under which the crystals were formed to have been not much greater than sufficient to counteract the elastic force of the vapour, he concluded that the nepheline may have been formed at a temperature of about 340° C. (644° Fahr.), or a very dull red heat only just visible in the dark. He estimated also from the fluid cavities in

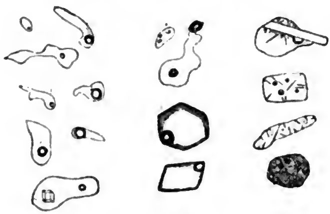

FIG. 7.—CAVITIES IN CRYSTALS, HIGHLY MAGNIFIED. A, LIQUID INCLUSIONS; B, GLASS INCLUSIONS; C, CAVITIES SHOWING THE DEVITRIFICATION OF THE ORIGINAL GLASS BY THE APPEARANCE OF CRYSTALS, ETC., UNTIL IN THE LOWEST FIGURE A STONY OR LITHOID PRODUCT IS FORMED.

the quartz of granite that this rock has probably consolidated at somewhat similar temperatures, under a pressure sometimes equal to that of 76,000 feet of rock.[1] Zirkel, however, has pointed out that even in contiguous cavities, where there is no evidence of leakage through fine fissures, the relative size of the vacuole varies within very wide limits, and in such a manner as to indicate no relation whatever to the dimensions of the enclosing cavities. Had the vacuole been due merely to the contraction of the liquid on cooling, it ought to have always been proportionate to the size of the cavity.[2]

MM. De la Vallée Poussin and Renard, attacking the question from another side, measured the relative dimensions of the vesicle and of its enclosed water and cube of rock-salt, as contained in the quartziferous diorite of Quenast in Belgium. The temperature at which the ascertained volume of water in the cavity would dissolve its salt was found by calculation to be 307° C. (520 Fahr.). But as the law of the solubility of common salt has not been experimentally determined for high temperatures, this figure can only be accepted

[1] Sorby, *op. cit.* pp. 480, 493. [2] *Mik. Beschaff.* p. 46.

provisionally, though other considerations go to indicate that it is probably not far from the truth. Assuming then that this was the temperature at which the vesicle was formed, these authors proceed to determine the pressure necessary to prevent the complete vaporisation of the water at that temperature, and obtain as the result a pressure of 87 atmospheres, equal to 84 tons per square foot of surface.[1] The great pressure under which many rocks were formed is well shown by the liquid carbon dioxide in the pores of their crystals.

Fluid inclusions may be dispersed at random through a crystal, or, as in the quartz of granite, gathered in intersecting planes (which look like fine fissures and which may sometimes have become real fissures owing to the line of weakness caused by the crowding of the cavities), or disposed regularly in reference to the contour of the crystal. In the last case they are sometimes confined to the centre, sometimes arranged in zones along the lines of growth of the crystal.[2] They are specially conspicuous in the quartz of granite and other massive rocks, as well as of gneiss and mica-schist; also in felspars, topaz, beryl, augite, nepheline, olivine, leucite and other minerals.

γ. Inclusions of glass or of some lithoid substance.—In many rocks which have consolidated from fusion, the component crystals contain globules or irregularly shaped enclosures of a vitreous nature (Fig. 7, Column B). These enclosures are analogous to the fluid-cavities just described. They are portions of the original glassy magma out of which the minerals of the rock crystallized, as portions of the mother-liquor are enclosed in artificially formed crystals of common salt. That magma is in reality a liquid at high temperatures, though at ordinary temperatures it becomes a solid. At first these glass vesicles may be confounded with the true liquid cavities which in some respects they closely resemble. But they may be distinguished by the immobility of their bubbles, of which several are sometimes present in the same cavity; by the absence of any diminution of the bubbles when heat is applied; by the elongated shape of many of the bubbles; by the occasional extrusion of a bubble almost beyond the walls of the vesicle, by the usual pale greenish or brownish tint of the substance filling the vesicle, and its identity with that forming the surrounding base or ground-mass in which the crystals are imbedded; but above all, by the complete passivity of the substance in polarized light. (See § vii., p. 188.)

Glass inclusions occur abundantly in some minerals, aggregated in the centre of a crystal or ranged along its zones of growth with singular regularity. They appear in felspars, quartz, leucite, and other crystalline ingredients of volcanic rocks, and of course prove

[1] *Mémoire sur les Roches dites Plutoniennes de la Belgique*, De la Vallée Poussin et A. Renard. *Acad. Roy. Belg.* 1876, p. 41. See also Ward, *Q. J. Geol. Soc.* xxxi. p. 568.
[2] The way in which vesicles, enclosed crystals, &c., are grouped along the zones of growth of crystals is illustrated in Fig. 5.

that these minerals, even the refractory quartz, have undoubtedly crystallized out of molten solutions.

In inclusions of a truly vitreous nature traces of devitrification may not infrequently be seen. In particular microscopic crystallites (p. 100) make their appearance, like those in the ground-mass of the rock. Sometimes the inclusions, like the general ground-mass, have an entirely stony character. This may be well observed in those inclusions which have not been entirely separated from the surrounding ground-mass, but are connected with it by a narrow neck at the periphery of the enclosing crystal. In some granites and in elvans the quartz by irregular contraction, while still in a plastic state, appears to have drawn into its substance portions of the surrounding already lithoid base;[1] but this appearance may sometimes be due to irregular corrosion of the crystals by the magma.[2]

δ. Crystals and crystalline bodies.—Many component minerals of rocks contain other minerals (Fig. 5). These occur sometimes as perfect crystals, more usually as what are termed microliths (p. 101). Like the glass-inclusions, they tend to range themselves in lines along the successive zones of growth in the enclosing mineral. Such microliths are of frequent occurrence in leucite, garnet, augite, hornblende, calcite, fluorite, &c. It is important to observe that the relative order of fusibility is not always followed in the microliths and enveloping crystals. Thus microliths of the easily fusible augite are in the Vesuvian lavas enclosed within the extremely refractory leucite.

ε. Filaments, streaks, patches, discolorations.—Besides the enclosures already enumerated, crystals likewise frequently enclose irregular portions of mineral matter, due to alteration of the original substance of the minerals or rocks. Thus tufts and vermicular aggregates of certain green ferruginous silicates are of common occurrence among the crystals and cavities of old pyroxenic volcanic rocks. Orthoclase crystals are often mottled with patches of a granular nature due to partial conversion of the mineral into kaolin. The magnetite, so frequently enclosed within minerals, is abundantly oxidized, and has given rise to brown and yellow patches and discolorations. Care must be taken not to confound these results of infiltrating water with the original characters of a rock. Practice will give the student confidence in distinguishing them, if he familiarises his eye with decomposition products by studying slices of the weathered parts of rocks.

B. GLASS.—Even to the unassisted eye, many volcanic rocks consist obviously in whole or in great measure of glass. This substance in mass is usually black or dark green, but when examined in thin sections under the microscope, it presents for the most part a pale brown tint, or is nearly colourless. In its purest condition it is quite structureless, that is, it contains no crystals, crystallites, or other distinguishable individualized bodies. But even in this state it may

[1] J. A. Phillips, *Q. J. Geol. Soc.* xxxi. p. 338.
[2] Fouqué et Lévy, *op. cit.*

sometimes be observed to be marked by clot-like patches or streaks of darker and lighter tint arranged in lines or eddy-like curves indicative of the flow of the original fluid mass. Rotated in the dark field of crossed Nicol prisms, such a natural glass remains dark, being perfectly inert in polarized light. It is therefore said to be *isotropic*, and may thus readily be distinguished from any enclosed crystals which acting on the light are *anisotropic* (p. 188). Perfectly homogeneous structureless glass without enclosures of any kind occurs for the most part only in limited patches, even in the most thoroughly vitreous rocks. Originally the structure of all glassy rocks at the time of most complete fusion may have been that of perfectly unindividualized glass. But as these masses tended towards a solid form, devitrification of their glass set in. Many forms of incipient or imperfect crystallization as well as perfect crystals were developed in the still fluid and moving mass, and were drawn out in the direction of motion. In some cases so far has devitrification proceeded, that no trace remains of any glass.

C. CRYSTALLITES.[1]—Under this name may be included minute

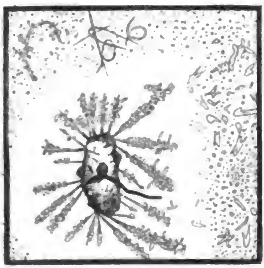

FIG. 8.—AUGITE CRYSTAL SURROUNDED BY MICROLITHS, FROM THE VITREOUS BASALT OF ESKDALE MUIR, MAGNIFIED 800 DIAMETERS.

inorganic bodies possessing a more or less definite form, but generally without the geometrical characters of crystals. They occur most commonly in rocks which have been formed from igneous fusion, but are found also in others which have resulted from or have been altered by aqueous solutions. They seem to be early or peculiar forms of crystallization developed in artificial slags, and in many vitreous rocks, under conditions not yet well understood. The

[1] This word was first used by Sir James Hall to denote the lithoid substance obtained by him after fusing and then slowly cooling various "whinstones" or volcanic rocks. Since its revival in lithology it has been applied to the minuter bodies above described, and a distinction has been drawn between crystallites and microliths. It seems to me most convenient to retain the term *crystallites* as the general designation of all the indefinitely crystalline or incipient forms of individualization among minerals, and to subdivide these by the employment of such names as Vogelsang's *Globulites*, *Longulites*, *Microliths*, &c. The student should consult this author's *Philosophie der Geologie*, p. 139; *Krystalliten*, Bonn, 8vo. 1875; also his descriptions in *Archives Néerlandaises* v. 1870, vi. 1871. Sorby, *Brit. Assoc.* 1880.

simplest are extremely minute drop-like bodies or *globulites*. Quite isotropic, they are sometimes crowded confusedly through the glass, giving it a dull or somewhat granular character, while in other cases they are arranged in lines or groups. Gradations can be traced from spherical or spheroidal globulites into other forms more elliptical in shape, but still having a rounded outline and sometimes sharp ends. These were termed by Vogelsang *Longulites*. There does not appear to be any essential distinction, save in degree of development, between these forms and the long rod-like or needle-shaped bodies which have been termed *microliths* (*Belonites*). Existing sometimes as mere simple needles or rods, these microliths may be traced into more complex forms, sometimes pointed, sometimes toothed at the end, straight, curved or coiled, smooth or striated, at one time solitary, at another in groups. It is sometimes possible from their association to determine to what minerals microliths belong. Augite, hornblende, apatite and felspars all occur in these rudimentary forms. In most

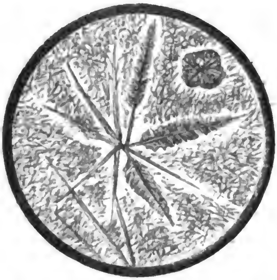

FIG. 9.—MICROLITHS OF THE PITCHSTONE OF ARRAN, MAGNIFIED 70 DIAMETERS. (See p. 140.)

cases the microliths are transparent and colourless, or slightly tinted, but sometimes they are black and opaque, from a coating of ferruginous oxide, or only appear so as an optical delusion from their position. Black seemingly opaque hair-like twisted and curved microliths, termed *trichites*, occur abundantly in obsidian. Good illustrations of the general characters and grouping of microliths are shown in some vitreous basalts. In Fig. 8, for example, the outer portion of the field displays crowded globulites and longulites, as well as here and there a few belonites and some curved and coiled microliths. Round the augite crystal these various bodies have been drawn together out of the surrounding glass. Numerous rod-like microliths diverge from the crystal, and these are more or less thickly crusted with the simpler and smaller forms.[1] In Fig. 9 the remarkably beautiful structure of an Arran pitchstone is shown; the glassy base being crowded with minute microliths which are grouped in a fine brush-like arrangement round tapering rods. In this case also we

[1] Geikie, *Proc. Roy. Phys. Soc. Edin.* v. p. 246, Plate v. Fig. 5.

see that the glassy base has been clarified round the larger individuals by the abstraction of the crowded smaller microliths.

With the crystallites may be grouped the characteristic amorphous or indefinitely granular and fibrous or scaly matter which constitutes the microscopic base in which the definite crystals of felsites and porphyries are imbedded (pp. 104, 135). The true nature of this substance is not yet understood. Between crossed Nicol prisms it sometimes behaves isotropically, like a glass, but in other cases allows a mottled glimmering light to pass through. It is a product of devitrification where, though the vitreous character has disappeared, its place has not been taken by recognizable crystals or crystalline particles.[1]

Every gradation in the relative abundance of crystallites may be traced. In some obsidians and other vitreous rocks, portions of the glass can be obtained with comparatively few of them; but in the same rocks we may not infrequently observe adjacent parts where they have been so largely developed as to usurp the place of the original glass, and give the rock in consequence a lithoid aspect (p. 141).

D. Detritus.—Many rocks are composed of the detritus of preexisting materials. In the great majority of cases this can be readily detected, even with the naked eye. But where the texture of such detrital or fragmental (clastic) rocks becomes exceedingly fine, their true nature may require elucidation with the microscope. An obvious distinction can be drawn between a mass of compact detritus and a crystalline or vitreous rock. The detrital materials are found to consist of variously and irregularly shaped grains with more or less of an amorphous and generally granular paste. In some cases the grains are broken and angular, in others they are rounded or waterworn (p. 154). They may consist of minerals (quartz, chert, felspars, mica, &c.), or of rocks (slate, limestone, basalt, &c.), or of the remains of plants or animals (spores of lycopods, fragments of shells, crinoids, &c.). It is evident therefore that though some of them may be crystalline, the rock of which they now form part is a non-crystalline compound. Where water containing carbonate of lime or other mineral matter in solution has permeated a detrital rock, it has sometimes allowed its dissolved materials to crystallize among the interstices of the detritus. But this change does not conceal the fundamentally secondary or derivative nature of the mass.

2. Microscopic Structures of Rocks.

We have next to consider the manner in which the foregoing microscropic elements are associated in rocks. This inquiry brings before us the minute structure of rocks, and throws great light upon their origin and history.[2]

[1] See Zirkel, *Mik. Beschaff.* p. 280. Rosenbusch, vol. ii. p. 60.

[2] The first broad classification of the microscopic structure of rocks was that proposed by Zirkel, which, with slight modification, is here adopted. *Mik. Beschaff.* p. 265. *Basaltgesteine*, p. 88.

Four types of rock-structure are revealed by the microscope. A, wholly crystalline; B, semi-crystalline; C, glassy; D, clastic.

A. WHOLLY CRYSTALLINE, consisting entirely of crystals or crystalline individuals, whether visible to the naked eye, or requiring

FIG. 10.—WHOLLY CRYSTALLINE STRUCTURE. GRANITE (20 Diameters).
The white portions are Quartz, the striped parts Felspar, the long, dark, finely striated stripes are Mica. (See p. 131.)

the aid of a microscope, imbedded in each other without any intervening amorphous substance. Rocks of this type are exemplified by granite (Fig. 10) and by other igneous rocks. But they occur also among the crystalline limestones and schists, as in statuary marble, which consists entirely of crystalline granules of calcite (Fig. 16).

FIG. 11.—SEMI-CRYSTALLINE STRUCTURE. DOLERITE, CONSISTING OF A TRICLINIC FELSPAR, AUGITE, AND MAGNETITE IN A DEVITRIFIED GROUND-MASS (20 Diameters)
The numerous oblong Prisms are triclinic Felspar; the broader monoclinic forms, slightly shaded in the drawing, are Augite; the black specks are Magnetite; the needle-shaped forms are Apatite. (See p. 148.)

B. SEMI-CRYSTALLINE.—This division probably comprehends the majority of the massive eruptive or igneous rocks. It is distinguished by the occurrence of what appears to the naked eye as a compact or finely granular ground-mass, through which more or less

recognizable crystals are scattered. Examined with the microscope, this ground-mass is found to present considerable diversity. It may be (1) wholly a glass, as in some basalts, trachytes, and other volcanic products; (2) partly devitrified through separation of peculiar little granules and needles which appear in a vitreous base; (3) still further devitrified, until it becomes an aggregation of such little granules, needles, and hairs between which little or no glass base appears (microcrystallitic); or (4) "microfelsitic," closely related to the two previous groups, and consisting of a nearly structureless mass, marked usually with indefinite or half effaced granules and filaments, but behaving like a singly refracting amorphous body.

C. Glassy.—Composed of a volcanic glass such as has already been described. It seldom happens, however, that rocks which seem to the eye to be tolerably homogeneous glass do not contain abundant microliths and minute crystals. Hence truly vitreous rocks tend to graduate into the second or semi-crystalline type. This gradation

Fig. 12.—Fluxion Structure in Obsidian. (20 Diameters. See p. 141.)

and the abundant evidence of traces of a devitrified base or magma between the crystals of a vast number of eruptive rocks, lead to the belief that the glassy type was the original condition of most if not all of these rocks. Erupted as molten masses, their mobility would depend upon the fluidity of the glass. Yet even while still deep within the earth's crust, some of their constituent minerals (felspars, leucite, magnetite, &c.) were often already crystallized, and suffered fracture and corrosion by subsequent action of the enclosing magma. This is well shown by what is termed the *fluxion-structure*. Crystals and crystallites are ranged in current-like lines, with their long axes in the direction of these lines. Where a large older crystal occurs, the train of minuter individuals is found to sweep round it and to reunite on the further side, or to be diverted in an eddy-like course (Fig. 12). So thoroughly is this arrangement characteristic of the motion of a somewhat viscid liquid, that there cannot be any doubt that such was the condition of these masses before their consolidation. The fluxion structure may be detected in many eruptive rocks,

from thoroughly vitreous compounds like obsidian, on the one hand, to completely crystalline masses like some dolerites on the other. It occurs not only in what are usually regarded as volcanic rocks, but also in plutonic or deep-seated masses which there is reason to believe consolidated deep beneath the surface, as for instance in the Bode vein of the Harz and among quartz-porphyries associated with granites in Aberdeenshire. The structure, therefore, cannot be regarded as certainly indicating that the rock in which it is found ever flowed out at the surface as lava.

The final stiffening of a vitreous mass into solid stone has resulted (1st) from mere solidification of the glass: this is well seen at the edge of dykes and intrusive sheets of different basalt rocks, where the igneous mass, having been suddenly congealed along its line of contact with the surrounding rocks, remains there in the condition of glass, though only an inch further inward from the edge the vitreous magma has disappeared, as represented in Fig. 29; (2nd) from the devitrification of the glass by the abundant development of microfelsitic granules and filaments, as in quartz-porphyry, or of crystallites and crystals, as in such glassy rocks as obsidian and tachylite; or (3rd) from the complete crystallization of the whole of the original glassy base, as may be observed in some dolerites and basalts.

D. CLASTIC.—Composed of detrital materials, such as have been already described (p. 102). Where these materials consist of grains of

FIG. 13.—CLASTIC STRUCTURE OF INORGANIC ORIGIN—SECTION OF A PIECE OF GREYWACKE. (10 Diameters. See p. 159.)

quartz-sand, they withstand almost any subsequent change, and hence can be recognized even among the most highly metamorphosed series of rocks (p. 155). Quartzite from such a series can sometimes be scarcely distinguished under the microscope from unaltered quartzose sandstone. Where the detritus has resulted from the destruction of aluminous or magnesian silicates, it is more susceptible of alteration. Hence it can be traced in regions of local metamorphism becoming more and more crystalline, until the rocks formed of or containing it pass into true crystalline schists.

Detritus derived from the comminution or decay of organic remains presents very different and characteristic structures.[1] Sometimes it is of a siliceous nature, as where it has been derived from diatoms and radiolarians. But most of the organically derived detrital rocks are calcareous, formed from the remains of foraminifera, corals, echinoderms, polyzoa, cirripedes, annelides, molluscs, crustacea and other invertebrates, with occasional traces of fishes or even of higher vertebrates. Distinct differences of microscopic structure can be detected in the hard parts of some of the living representatives of these forms, and similar differences have been detected in beds of limestone of all ages. Mr. Sorby, in the paper cited below, has shown how characteristic and persistent are some of these distinctions, and how they may be made to indicate the origin of the rock in which they occur. There is an important difference between the two forms, in which carbonate of lime is made use of by invertebrate animals;

Fig. 14.—Clastic Structure of Organic Origin—Structure of Chalk (Sorby). Magnified 100 Diameters. (See p. 168.)

aragonite being much less durable than calcite. Hence while shells or other organisms formed largely or wholly of aragonite crumble down into a mere amorphous mud, pass into crystalline calcite, or disappear, the fragments of those consisting of calcite may remain quite recognizable.

It is evident therefore that the absence of all trace of organic structure in a limestone need not invalidate an inference from other evidence that the rock has been formed from the remains of organisms. The calcareous organic débris of a sea-bottom may be disintegrated and reduced to amorphous detritus by the mechanical action of waves and currents, by the solvent chemical action of the water, by the decay of the binding material, as of the organic matter of shells, or by being swallowed and digested by other animals.[2]

[1] The student who would further investigate this subject will find a suggestive and luminous essay upon it by Mr. Sorby in a recent presidential address to the Geological Society. *Quart. Journ. Geol. Soc.* 1879.

[2] Sorby, *loc. cit.*

Moreover, in clastic calcareous rocks, owing to their liability to alteration by infiltrating water, there is a tendency to acquire an internal crystalline texture. At the time of formation little empty spaces lie between the component granules and fragments, and according to Mr. Sorby, these interspaces may amount to about a quarter of the whole mass of the rock. They have very commonly been filled up by calcite introduced in solution. This infiltrated calcite acquires a crystalline structure like that of ordinary mineral veins. But the original component organic granules also themselves become crystalline, and, save in so far as their external contour may reveal their original organic source, they cannot be distinguished from mere mineral grains. In this way a cycle of geological change is completed. The calcium carbonate orginally dissolved out of rocks by infiltrating water and carried into the sea is secreted from the oceanic waters by corals, foraminifera, echinoderms, molluscs and other invertebrates. The remains of these creatures collected on the sea-bottom slowly accumulate into beds of detritus, which in after times are upheaved into land. Water once more percolating through the calcareous mass gradually imparts to it a crystalline structure, and eventually all trace of organic forms may be effaced. But at the same time the rock once exposed to meteoric influences is attacked by carbonated water, its molecules are carried in solution into the sea, where once again they will be built up into the framework of marine organisms.

E. ALTERATION OF ROCKS.—One of the most important revelations of the microscope is the extent to which rocks have undergone alteration through the influence of infiltrating water. The nature of some of these changes is described in subsequent pages. It may be sufficient to note here a few of the more obvious proofs of alteration. Threads and kernels of calcite running through an eruptive rock, such as granite, dolerite, or trachyte, are a good index of internal decomposition. They usually point to the decay of some lime-bearing mineral in the rock. Some other minerals are likewise frequent signs of alteration, such as serpentine (often resulting from the alteration of olivine, see Fig. 6), chlorite, epidote, limonite. In many cases, however, the decomposition products are so indefinite in form and so minute in quantity, as not to permit of their being satisfactorily referred to any known species of mineral. For these indeterminate but frequently abundant substances, the following convenient short names have been proposed by Vogelsang to save periphrasis, until the true nature of the substance is ascertained. *Viridite*—green transparent or translucent patches, often in scaly or fibrous aggregations, of common occurrence in more or less decomposed rocks containing hornblende, augite, or olivine: probably in many cases serpentine, in others chlorite or delessite. *Ferrite*—yellowish, reddish, or brownish amorphous substances, probably consisting of peroxide of iron either hydrous or anhydrous, but not certainly referable to any mineral, though sometimes pseudomorphous after

ferruginous minerals. *Opacite*—black, opaque grains and scales of amorphous earthy matter, which may in different cases be magnetite, or some other metallic oxide, earthy silicates, graphite, &c.[1]

§ V.—*Classification of Rocks.*

It is evident that lithology may be approached from two very different sides. We may on the one hand regard rocks as so many masses of mineral matter, presenting great variety of chemical composition and marvellous diversity of microscopic structure. Or on the other hand, passing from the details of their chemical and mineralogical characters, we may look at them as the records of ancient terrestrial changes. In the former aspect, they present for consideration problems of the highest interest in inorganic chemistry and mineralogy; in the latter view they invite attention to the great geological revolutions through which the planet has passed. It is evident therefore that two distinct systems of classification may be followed, the one based on chemical and mineralogical, the other on geological considerations.

From a chemical point of view, rocks may be grouped according to their composition; as *oxides*, exemplified by formations of quartz, hæmatite, or magnetite; *carbonates*, including the limestones and clay-ironstones; *silicates*, embracing the vast majority of rocks, whether composed of a single mineral, or of more than one; *phosphates*, such as guano and the older bone beds and coprolitic deposits. A classification of this kind, however, pays no regard to the mode of origin or conditions of occurrence of the rocks, and is quite unsuited for the purposes of the geologist.

From the mineralogical side, rocks may be classified with reference to their prevailing mineral constituent. Thus such subdivisions as Calcareous rocks, Quartzose rocks, Orthoclase rocks, Plagioclase rocks, Pyroxenic rocks, Hornblendic rocks, &c., may be adopted; but these are hardly less objectionable to the geologist, and are in fact suited rather for the arrangement of hand-specimens in a museum, than for the investigation of rocks *in situ*.

From the standpoint of geological inquiry, rocks have been classified according to their mode of origin. In one system they are arranged under three great divisions: 1st, *Igneous*, embracing all which have been erupted from the heated interior of the earth; 2nd, *Aqueous* or *Sedimentary*, including all which have been laid down as mechanical or chemical deposits from water or air, and all which have resulted from the growth and decay of plants or animals; 3rd, *Metamorphic*, those which have undergone subsequent change within the crust of the earth, whereby their original character has been so modified, as to be sometimes quite indeterminable. Another geological arrangement is based upon the general structure of

[1] Vogelsang, *Z. Deutsch. Geol. Ges.* xxiv. (1872) p. 529. Zirkel, *Geol. Expl. 40th Parallel*, vol. vi. p. 12.

the rocks, and consists of two divisions, 1st, *Stratified*, embracing all the aqueous and sedimentary with part of the less altered metamorphic rocks; 2nd, *Unstratified*, nearly conterminous with the term igneous, since it includes all the eruptive rocks. Further subdivisions of this series have been proposed according to differences of structure or texture, as *porphyritic*, *granitic*, &c. These geological subdivisions, however, ignore the chemical and mineralogical characters of the rocks, and are based on deductions which may not always be sound. Thus rocks may be included in the igneous series which further research may show not to be of igneous origin; others may be classed as metamorphic, regarding the true origin of which there may be considerable uncertainty. A further system of classification based upon relative age has been applied to the arrangement of the eruptive rocks, those masses which were erupted prior to the close of Secondary time being classed as "older," and those of later date as "younger." This system has recently been elaborated in great detail by Michel-Lévy, who maintains that the same types have been reproduced nearly in the same order in the two series, though basic rocks, often with vitreous characters, rather predominate in the later. But it can be shown that some rocks occur in both series, and though there are undoubtedly well-marked differences between some Tertiary and pre-Tertiary eruptive rocks, it may be doubted whether this classification is not too ingenious and artificial.[1]

Though no classification which can at present be proposed is wholly satisfactory, one which shall do least violence at once to geological and mineralogical relationships is to be preferred. Avoiding therefore all theoretical considerations based on deductions as to the origin of rocks, we may conveniently make use of the broad distinction between Crystalline (including vitreous) and Clastic or Fragmental rocks. The former are, 1st, stratified, including chiefly chemical deposits, such as limestones, dolomites, sinters, &c.; 2nd, schistose, embracing most of the so-called metamorphic rocks; 3rd, massive: this series is nearly coincident with the old division of Igneous Rocks. The Clastic or Fragmental rocks are formed either of the débris of older rocks, or of the aggregated remains of plants or animals. In some cases, as for example, in limestones of organic origin, subsequent alteration gradually effaces the fragmental structure, and superinduces a true crystalline internal arrangement. Hence along certain lines fragmental rocks pass gradually into the stratified crystalline series.

It must be kept in view that in this proposed system of classification, and in the following detailed description of rocks, many questions regarding the origin and decomposition of these mineral masses must necessarily be alluded to. The student, however,

[1] See on this subject, J. D. Dana, *Amer. J. Sci.* xvi. 1878, p. 336. Compare also Michel-Lévy, *Bull. Soc. Géol. France*, iii. 3rd ser. p. 199, vi. p. 173. Fouqué et Michel-Lévy, *op. cit.* p. 150. Rosenbusch, *Mik. Physiog.* ii. On the classification of compound silicated rocks, see Vogelsang, *Z. Deutsch. Geol. Ges.* xxiv. p. 507, and for an incisive criticism of too merely mineralogical classification, Lossen, *op. cit.* xxiv. p. 782.

will find these questions discussed in later pages, and will probably recognise a distinct advantage in this unavoidable reference to them in connection with the rocks by which they are suggested.

§ VI.—*A Description of the more Important Rocks of the Earth's Crust.*

Full details regarding the composition, microscopic structure, and other characters of rocks must be sought in such general treatises and special memoirs as those already cited (pp. 86, 94). The purposes of the present text-book will be served by a succinct account of the more common or important rocks which enter into the composition of the crust of the earth.

A. Crystalline (including Vitreous).

1. Stratified.

This division consists mainly of chemical deposits, but includes also some which, originally formed of organic calcareous débris, have acquired a crystalline structure. The rocks included in it occur as laminæ and beds usually intercalated among clastic formations, such as sandstone and shale. Sometimes they attain a thickness of many thousand feet, with hardly any interstratification of mechanically derived sediment. They are being formed abundantly at the present time by mineral springs and on the floors of inland seas; while on the bottom of lakes and of the main ocean calcareous organic accumulations are in progress which will doubtless eventually acquire a thoroughly crystalline structure like that of many limestones.

Ice.—So large an area of the earth's surface is covered with ice, that this substance deserves notice among geological formations. Ice is commonly and conveniently classified in two divisions, snow-ice and water-ice, according as it results from the compression and alternate melting and freezing of fallen snow, or from the freezing of the surface or bottom of sheets of water.

Snow-ice is of two kinds. 1st, Fallen snow on mountain slopes above the snow-line gradually assumes a granular structure. The little crystalline needles and stars of ice are melted and frozen into rounded granules, which form a more or less compact mass known in Switzerland as *Névé* or *Firn.* 2nd, When the granular névé slowly slides down into the valleys, it acquires a more compact crystalline structure and becomes *glacier-ice.* The structure and movements of glaciers are described in Book III. Part ii. Glacier-ice in small fragments is white or colourless, and often shows innumerable fine bubbles of air, sometimes also fine particles of mud. In larger masses it has a blue or green-blue tint, and displays a veined structure consisting of parallel vertical veinings of white ice full of air-bubbles, and of blue clear ice without air-bubbles. Snow-ice is formed above the snow-line, but may descend in glaciers far below it. It covers large areas of the more lofty mountains of the globe,

even in tropical regions. Towards the poles it descends to the sea-level, where large pieces of it break off and float away as icebergs.

Water-ice is formed, 1st, by the freezing of the surface of fresh-water (river-ice, lake-ice), or of the sea (ice-foot, floe-ice, pack-ice); this is a compact, clear, white or greenish ice. 2nd, by the freezing of the layer of water lying on the bottom of rivers, or the sea (bottom-ice, ground-ice, anchor-ice); this variety is more spongy, and often encloses mud, sand and stones.

Rock Salt (Sel gemme, Steinsalz) occurs in layers or beds from less than an inch to more than six hundred feet in thickness. The salt deposits at Stassfurt, for example, are 1197 feet thick, of which the lowest beds comprise 685 feet of pure rock salt, with thin layers of anhydrite ¼ inch thick dividing the salt at intervals of from one to eight inches. The more insoluble salts are found in the lower parts of the saliferous series and disappear towards the top. When purest, rock salt is clear and colourless, but usually is coloured red (peroxide of iron); sometimes green, or blue. It varies in structure, being sometimes beautifully crystalline and giving a cubical cleavage; laminated, granular, or less frequently fibrous. It always contains some admixture, either mechanical (clay, sand, vesicles of combustible gas, sometimes present in large quantity, or saline water) or chemical (chlorides of magnesium, or of calcium, &c.). Occasionally remains of minute forms of vegetable and animal life, bituminous wood, corals, shells, crustaceans, and fish teeth are met with in it. Microscopic examination shows it to contain minute cubical cavities filled with a solution of salt. Owing to its ready solubility, it is not found at the surface in moist climates. With its associated seams of gypsum, anhydrite, red clay, &c., it forms series of strata several thousand feet thick, as in Gallicia. It has been formed by the evaporation of very saline water in enclosed basins—a process going on now in many salt-lakes (Great Salt Lake of Utah, Dead Sea), and on the surface of some deserts (Kirgis Steppe). In different parts of the world deposits of salt have probably always been in progress from very early geological times. Saliferous formations of Tertiary and Secondary age are abundant in Europe, while in America they occur even in rocks as ancient as the Upper Silurian period, and among the Punjab Hills in still more ancient strata.

Limestone (Calcaire, Kalkstein).—Essentially a mass of calcium carbonate, sometimes nearly pure, and entirely or almost entirely soluble in hydrochloric acid, sometimes loaded with sand, clay, or other intermixture. Few rocks vary more in texture and composition. It may be a hard flinty close-grained mass, breaking with a splintery or conchoidal fracture; or a crystalline rock built up of fine crystals of calcite and resembling loaf sugar in colour and texture; or a dull earthy friable chalk-like deposit; or a compact massive finely-granular rock resembling a close-grained sandstone or freestone. The colours, too, vary extensively, the most common being shades of blue-grey and cream-colour passing into white. Some limestones

are highly siliceous, the calcareous matter having been accompanied with silica in the act of deposition; others are argillaceous, sandy, ferruginous, dolomitic, or bituminous. By far the larger number of limestones are of organic origin; though owing to internal re-arrangement their original clastic character has frequently been changed into a crystalline one. Under the present subdivision are placed all those limestones which have had a distinctly chemical origin, and also those which, though doubtless, in many cases, originally formed of organic débris, have lost their fragmental, and have assumed instead a crystalline structure.

Compact, common limestone.—A fine grained crystalline granular aggregate, occurring in beds or laminæ interstratified with other aqueous deposits. When purest it is readily soluble in acid with effervescence, leaving little or no residue. Many varieties occur, to some of which separate names are given. *Hydraulic limestone* contains 10 per cent. or more of silica (and usually alumina) and, when burnt and subsequently mixed with water, forms a cement or mortar, which has the property of "setting" or hardening under water. Limestones containing perhaps as much as 25 per cent. of silica, alumina, iron, &c., which in themselves would be unsuitable for many of the ordinary purposes for which limestones are used, can be used for making hydraulic mortar. These limestones occur in beds like those in the Lias of Lyme Regis, or in nodules like those of Sheppey, from which Roman cement is made. *Cement-stone* is the name given to many pale dull ferruginous limestones, which contain an admixture of clay, and some of which can be profitably used for making hydraulic mortar or cement. *Fetid limestone* (*stinkstein, swinestone*) gives off a fetid smell (sulphuretted hydrogen gas), when struck with a hammer. In some cases the rock seems to have been deposited by volcanic springs containing decomposable sulphides as well as lime. In other instances the odour may be connected with the decomposition of imbedded organic matter. In some quarries in the Carboniferous Limestone of Ireland, as mentioned by Mr. Jukes, the freshly broken rock may be smelt at a distance of a hundred yards when the men are at work, and occasionally the stench becomes so strong that the workmen are sickened by it, and require to leave off work for a time. *Cornstone* is an arenaceous or siliceous limestone particularly characteristic of some of the Palæozoic red sandstone formations. *Rottenstone* is a decomposed siliceous limestone from which most or all of the lime has been removed, leaving a siliceous skeleton of the rock. A similar decomposition takes place in some ferruginous limestones, with the result of leaving a yellow skeleton of ochre.

Travertine (calcareous tufa) is the material deposited by calcareous springs, usually white or yellowish, varying in texture from a soft chalk-like substance or marl to a compact building-stone. *Stalactite* is the name given to the calcareous pendant deposit formed on the roofs of limestone-caverns, vaults, bridges, &c.; while the

water from which the hanging lime-icicles are derived drips to the floor, and on further evaporation there gives rise to the crust-like deposit known as *stalagmite*. Mr. Sorby has shown that in the calcareous deposits from fresh water there is a constant tendency towards the production of calcite crystals with the principal axis perpendicular to the surface of deposit. Where that surface is curved, there is a radiation or divergence of the fibre-like crystals. This is well seen in sections of stalactites and of some calcareous tufas (Fig. 100).

Oolite.—A granular limestone, in which the grains are more or less perfectly spherical, giving the aspect of fish-roe. Each grain consists of successive concentric coats of carbonate of lime formed round some minute grain of sand or other foreign body which was kept in motion, so that all sides could in turn become encrusted. Oolitic grains of this character are now forming in the springs of Carlsbad (Sprudelstein); but they may no doubt also be produced

FIG. 15.—MICROSCOPIC STRUCTURE OF OOLITIC LIMESTONE, AFTER SORBY. MAGNIFIED 30 DIAMETERS.

where gentle currents in lakes or partially enclosed areas of the sea keep grains of sand or fragments of shells drifting along in water, which is so charged with lime as to be ready to deposit it upon any suitable surface. Where the individual grains of an oolitic limestone are as large as peas, the rock is called a pisolite.

Marble (granular limestone).—A crystalline-granular aggregate composed of crystalline calcite granules of remarkably uniform size, each of which has its own independent twin lamellæ (often giving interference colours) and cleavage lines. This characteristic structure is well displayed when a thin slice of ordinary statuary marble is placed under the microscope (Fig. 16). Typical marble is white, but also yellow, grey, blue and red; or streaked and mottled. Its granular structure gives it a resemblance to loaf-sugar, whence the term "saccharoid" applied to it. Fine silvery scales of mica or talc may often be noticed even in the purest marble. Some crystalline limestones associated with gneiss and schist

are peculiarly rich in minerals,—mica, garnet, tremolite, actinolite, anthophyllite, zoisite, vesuvianite, and many other species occurring there often in great abundance. Many varieties of colour and texture occur among these limestones, as may be seen in the numerous kinds of ornamental marble.

Marble is regarded by most geologists as a metamorphic rock, that is, one in which the calcium carbonate, whether derived from an organic or inorganic source, has been entirely recrystallized *in situ.* In the course of this change the original clay sand or other impurities of the rock have been also crystallized, and now appear as the crystalline silicates just referred to. Marble occurs in beds and large lenticular masses associated with crystalline schists on many different geological horizons. In Canada it occurs of Laurentian; in Scotland of Lower Silurian; in Utah of Upper Carboniferous; in Southern Europe of Jurassic age.

Fig. 16.—Microscopic Structure of White Statuary Marble. Magnified 50 Diameters.

Dolomite (Magnesian Limestone) consists typically of a yellow or white crystalline massive aggregate of the mineral dolomite; but the relative proportions of the calcium and magnesium carbonates vary indefinitely, so that every gradation can be found, from pure limestone without magnesium carbonate up to pure dolomite containing 45·65 per cent. of that carbonate. Ferrous carbonate is also of common occurrence in this rock. The texture of dolomite is usually distinctly crystalline, the individual crystals being occasionally so loosely held together that the rock readily crumbles into a crystalline sand. A fissured cavernous structure is of common occurrence; even in compact varieties cellular spaces occur lined with crystallized dolomite (Rauchwacke), the crystals of which are often hollow and sometimes enclose a kernel of calcite. Other varieties are built up of spherical, botryoidal and irregularly-shaped concretionary masses. Dolomite in its more typical forms is distinguishable from limestone by its greater hardness (3·5—4·5), higher specific gravity (2·8—2·95), and

much less solubility in hydrochloric acid. It occurs sometimes in beds of original deposit associated with gypsum, rock-salt and other results of the evaporation of saturated saline waters; it is also found replacing what was once ordinary limestone. This process, in which carbonate of lime is replaced by carbonate of magnesia, is known as *dolomitization* (see Book III., Part I., Section iv., § ii.).[1] Dolomite forms huge mountain masses, as in the Dolomite Mountains of the Eastern Alps.

Gypsum.—A fine granular to compact, sometimes fibrous or sparry aggregate of the mineral gypsum, having a hardness of only 1·5—2 (therefore scratched with the nail), and unaffected by acids; hence readily distinguishable from limestone, which it occasionally resembles. It is normally white, but may be coloured grey or brown by an admixture of clay or bitumen, or yellow and red by being stained with iron oxide. It occurs in beds, lenticular intercalations and strings, usually associated with beds of red clay, rock-salt, or anhydrite, in formations of many various geological periods from the Silurian (New York) down to recent times. The Triassic gypsum deposits of Thuringia, Hanover and the Harz have long been famous. One of them runs along the south flank of the Harz Mountains as a great band six miles long and reaching a height of sometimes 430 feet.

Gypsum furnishes a good illustration of the many different ways in which some mineral substances can originate. Thus it may be produced, 1st, as a chemical precipitate from solution in water, as when sea-water is evaporated; 2nd, through the decomposition of sulphides and the action of the resultant sulphuric acid upon limestone; 3rd, through the mutual decomposition of carbonate of lime and sulphates of iron, copper, magnesia, &c.; 4th, through the hydration of anhydrite; 5th, through the action of the sulphurous vapours and solutions of volcanic orifices upon limestone and calcareous rocks.[2] It is in the first of these ways that the thick beds of gypsum associated with rock-salt in many geological formations have been formed. The first mineral to appear in the evaporation of sea-water being gypsum, it has been precipitated on the floors of inland seas and saline lakes before the more soluble salts.

Anhydrite.—The anhydrous variety of calcium sulphate occurs in saliferous deposits, but is less frequent than gypsum, into which it passes by taking up 0·2625 of its weight of water.[3]

Ironstone.—Under this general term are included a number of iron ores in which the peroxide, protoxide and carbonate enter in various mixtures with clay and other impurities. They have generally been deposited as chemical precipitates on the bottoms of

[1] On the mineralogical nature of dolomite see O. Meyer, *Z. Deutsch Geol. Ges.* xxxi. p. 445, Loretz, *op. cit.* xxx. p. 387, xxxi. p. 756.

[2] Roth. *Chem. Geol.* i. p. 553.

[3] See G. Rose on formation of this rock in presence of a solution of chloride of sodium. *Neues Jahrb. Min.* 1871, p. 932. Also Bischof, *Chem. und Phys. Geol.* Suppl. (1871) p. 188.

lakes, under marshy ground, or within fissures and cavities of rocks. Some of the iron ores might be placed with the schistose rocks; but they are taken here for convenience.

Hæmatite (red iron-ore), a compact, fine-grained, earthy, or fibrous rock of a blood-red to brown-red colour, but where most crystalline, steel-grey and splendent, with a distinct cherry-red streak. Consists of anhydrous ferric oxide, but usually is mixed with clay, sand, or other ingredient, in such varying proportions as to pass, by insensible gradations, into ferruginous clays, sands, quartz, or jasper. Occurs as beds, huge concretionary masses, and veins traversing crystalline rocks; sometimes, as in Westmoreland, filling up cavernous spaces in limestone.

Limonite (brown iron-ore), an earthy or ochreous, compact, fine-grained or fibrous rock of an ochre yellow to a dark-brown colour, distinguishable from hæmatite by being hydrous and giving a yellow streak. Occurs in beds and veins, sometimes as the result of the oxidation of ferrous carbonate, also abundantly on the floors of some lakes and under marshy soil, where it forms a hard brown crust upon the impervious subsoil (*bog iron-ore*). Found likewise in oolitic concretions sometimes as large as walnuts, consisting of concentric layers of impure limonite with sand and clay (*Bohnerz*). See p. 174, and Book III. Part II. Section iii.

Spathic Iron-ore, a coarse or fine crystalline aggregate of the mineral siderite or ferrous carbonate, usually with carbonates of calcium, manganese and magnesium; has a prevalent yellowish or brownish colour, and when fresh, its rhombohedral cleavage faces show a pearly lustre, which soon disappears as the surface is oxidised into limonite. Occurs in beds and veins, especially among older geological formations. The colossal Erzberg at Eisenerz in Styria, which rises 2600 feet above the valley, consists almost wholly of siderite.[1]

Clay-ironstone (Sphærosiderite), a dull brown or black compact form of siderite with a variable mixture of clay, and usually also of organic matter. Occurs in the Carboniferous and other formations in the form either of nodules, where it has usually been deposited round some organic centre, or of beds interstratified with shales and coals. It is more properly described at p. 175, with the organically derived rocks.

Magnetic iron-ore, a granular to compact aggregate of magnetite, of a black colour and streak, more or less perfect metallic lustre, and strong magnetism. H. 5·5 to 6·5, Gr. 4·9 to 5·2. Commonly contains admixtures of other minerals, notably of hæmatite, chrome-iron, titanic-iron, pyrites, chlorite, quartz, hornblende, garnet, epidote, felspar. Occurs in beds and enormous lenticular masses (Stöcke) among crystalline schists. Thus among the gneisses of Norway lies the iron mountain of Gellivara in Luleo, Lappmark, 16,000 feet long, 8000 feet broad, and 2000 feet high.

[1] Zirkel, *Lehrb.* i. p. 345.

Siliceous Sinter (Geyserite, Kieselsinter), the siliceous deposit made by hot springs, including varieties that are crumbling and earthy, compact and flinty, finely laminated and shaly, sometimes dull and opaque, sometimes translucent, with pearly or waxy lustre. The deposit may occur as an incrustation round the orifices of eruption, rising into dome shaped or even columnar elevations, or investing leaves and stems of plants, shells, insects, &c., or hanging in pendent stalactites from cavernous spaces which are from time to time reached by the hot water. When purest, it is of snowy whiteness, but is often tinted yellow or flesh colour. It consists of silica 84 to 91 per cent., with small proportions of alumina, ferric oxide, lime, magnesia, and alkali, and from 5 to 8 per cent. of water.

Flint (Silex, Feuerstein).—A grey or black excessively compact rock with the hardness of quartz and a perfect conchoidal fracture, its splinters being translucent on the edges. Consists of an intimate mixture of crystalline insoluble silica and of amorphous silica soluble in caustic potass. Its dark colour, which can be destroyed by heat, arises chiefly from the presence of carbonaceous matter. Flint occurs principally as nodules, dispersed in layers through the upper chalk of England and the north-west of Europe. It frequently encloses organisms such as sponges, echini and brachiopods, and has been deposited from sea-water, at first through organic agency, and subsequently by direct chemical precipitation round the already deposited silica. (Book III. Part II. Section iii.) *Chert* is a name applied to impure varieties of flint, other brittle varieties are known as *hornstone*, which, under the microscope, however, presents a crystalline structure.

Some of the other varieties of silica occurring in large masses may be classed as rocks. Such are *jasper*, *common quartz*, and *ferruginous quartz*. These occur as veins traversing both stratified and unstratified rocks; also as beds associated with the crystalline schists. With them may be grouped *Lydian-stone*, a black or dark coloured, excessively compact, hard, infusible rock, with splintery fracture, occurring in thin, sharply defined bands, split by cross joints into polygonal fragments, which are sometimes cemented by fine layers of quartz. It consists of a mixture of silica with alumina, carbonaceous materials, and oxide of iron. It occurs in bands in the Silurian and later palæozoic formations interstratified with ordinary sandy and argillaceous strata. As these rocks have not been altered the bands of Lydian-stone may be of original formation, though the extent to which they are often veined with quartz shows that they have in many cases been permeated by siliceous water since their deposit.

Quartzite is a granular and compact aggregate of quartz, which has been produced by the metamorphism of sandstone. It will be described in connection with the schistose rocks among which it so frequently occurs.

2. Schistose or Foliated.

The Crystalline Schists form a remarkably well-defined series of rocks. Their structure is crystalline, but is distinguished from that of the massive rocks by the possession of an arrangement into more or less closely parallel layers or folia, consisting of materials which have assumed a crystalline character along these layers. The folia may be composed of only one mineral, but usually consist of two or more, which occur either in distinct, often alternate, laminæ or intermingled in the same layer. In some respects this structure

Fig. 17.—Profile of a piece of Gneiss, showing the lenticular character of its Folia, natural size.

resembles that of the stratified rocks, but is differentiated (1) by a prevalent striking want of continuity in the folia which, as a rule, are conspicuously lenticular, thickening out and then dying away, and reappearing after an interval on the same or a different plane (Fig. 17); (2) by a peculiar and very characteristic welding of the folia into each other, the crystalline particles of one layer being so intermingled with those of the layers above and below it that the whole coheres as a tough not easily fissile mass; (3) by a frequent remarkable and eminently distinctive puckering or crumpling of the

folia, which becomes sometimes so fine as to be discernible only under the microscope[1] (Fig. 19), but is often present conspicuously in hand-specimens (Fig. 18), and can be traced in increasing dimensions till it connects itself with gigantic curvatures of the strata which embrace whole mountains in their sweep. These characters are sufficient to indicate a great difference between schistose rocks and ordinary stratified formations, in which the strata lie in continuous flat, parallel, and more or less easily separable layers.

FIG. 18.—VIEW OF A HAND SPECIMEN OF CONTORTED MICA SCHIST, TWO-THIRDS NATURAL SIZE.

A rock possessing this crystalline arrangement into separate folia is termed a "schist." This word, though employed as a general designation to describe the structure of all truly foliated rocks, is also made use of as a suffix to the names of the minerals of which some of the foliated rocks largely consist. Thus we have "mica-schist," "chlorite schist," "hornblende-schist." If the mass loses its fissile tendency owing to the felting together of the component mineral into

[1] On the microscopic structure of the crystalline schists see Zirkel, *Microscopical Petrography* (vol vi. of King's *Exploration of 40th Parallel*) 1876, p. 14. Allport, *Q. J. Geol. Soc.* xxxii. p. 407. Sorby, *op. cit.* xxxvi. p. 81.

a tough coherent whole, the word rock is usually substituted for schist, as in "hornblende-rock," "actinolite-rock," and so on. The student must bear in mind that while the possession of a foliated structure is the distinctive character of the crystalline schists, it is not always present in every individual bed or mass associated with these rocks. Yet the non-schistose portions are so obviously integral parts of the schistose series that they cannot without great violation of natural affinities be separated from them. Hence in the following enumeration they are included as common accompaniments of the schists. For the same reason quartz-rock is placed in this subdivision, though it only occasionally shows a schistose structure. The origin of the crystalline schists has been the subject of long discussion among geologists. Werner held that, like other rocks of high antiquity, they were chemical precipitates from a universal ocean. Hutton and his followers maintained that they were mechanical aqueous sediments altered by subterranean heat. These two doctrines in various modifications are still maintained by opposite

Fig. 19.—Contorted Micaceous-schist, as seen under the Microscope with a magnifying power of 50 Diameters.

schools. Some schists are undoubtedly altered sedimentary rocks, and may properly be termed "metamorphic." Whether this has also been the origin of certain ancient gneisses and schists underlying the oldest fossiliferous formations is less easily determined. (See Book IV., Sect. viii).

Talc-schist.—A schistose aggregate of scaly talc, often with quartz, felspar, and other minerals; having an unctuous feel, and white or greenish colour. Occurs in beds associated with mica-schist and clay-slate, and frequently contains magnetite, chlorite, mica, kyanite, and other minerals, including carbonates. A massive variety composed of a finely felted aggregate of scales of talc with chlorite and serpentine is called potstone (Topfstein). Many rocks have been classed as talc-schist, which contain no talc but a hydrous mica. These are called by Dana hydro-mica-schists. Talc-schist

is not specially abundant, though it occurs in considerable mass in the Alps (Mont Blanc, Monte Rosa, Carinthia, &c.), and is found also among the Apennine and Ural mountains.

Chlorite-schist.—A scaly schistose aggregate of greenish chlorite usually with quartz and often with felspar, talc, mica, or magnetite, the last-named mineral frequently appearing in beautifully perfect disseminated octohedra. Occurs with gneiss and other schists in evenly bedded masses.

Hornblende-schist.—A schistose mass of black or dark-green hornblende, but often interleaved with felspar, quartz, or mica. When the schistose character disappears the mass becomes a hornblende-rock (amphibolite). When the variety actinolite occurs instead of common hornblende it forms actinolite-schist. These hornblende rocks occur as bands associated with gneiss and other schistose formations. It was suggested by the late Mr. Jukes that they may possibly represent what were once beds of hornblendic or augitic lava and tuff which have been metamorphosed together with the strata among which they were intercalated.

Clay-slate, argillaceous-schist (Argillite, Phyllite, Schiste ardoise, Thonschiefer, Thonglimmerschiefer). Under these names are included certain hard fissile argillaceous masses composed primarily of compact clay, with usually minute flakes of mica, fine granules of quartz, and frequently cubes and concretions of pyrites as well as veins of quartz and calcite. The fissile structure is specially characteristic. In some cases this structure is merely that of original deposit, as is proved by the alternation of fissile beds with bands of hardened sandstone or even conglomerate. Such are the argillaceous schists of the Scottish Highlands. But in certain regions where the rocks have been much compressed the fissile structure of the argillaceous bands is independent of stratification, and can be seen traversing it. Sorby has shown that this superinduced fissility or "cleavage" has resulted from an internal rearrangement of the particles in planes perpendicular to the direction in which the rocks have been compressed (See Book II. Section iv. § iii). In England the term "slate" or "clay-slate" has generally been applied solely to argillaceous rocks possessing this cleavage-structure. Those where the fissility is that of original sedimentation may be called "argillaceous schists."

Microscopic examination shows that while some argillaceous rocks consist mainly of granular kaolin, many cleaved clay-slates contain a large proportion of a micaceous mineral in extremely minute flakes which in the best Welsh slates have an average size of $\frac{1}{1000}$ of an inch in breadth, and $\frac{1}{6000}$ of an inch in thickness, together with very fine black hairs which may be magnetite.[1] Moreover, many clay-slates, though to outward appearance thoroughly non-crystalline and evidently of fragmental composition and sedimentary

[1] Sorby, *Q. J. Geol. Soc.* xxxvi. p. 68. See also a paper on the microscopic structure of Huronian clayslates by A. Wichman, *op. cit.* xxxv. p. 156.

origin, yet contain, sometimes in remarkable abundance, microscopic microliths and crystals of different minerals. These minute bodies consist of yellowish-brown needles possibly of hornblende, greenish or yellowish flakes of mica, also scales of calcite. They are generally placed with their long axes parallel with the lines of fissility. Small granules of quartz containing fluid-cavities, may possibly be of clastic derivation, but they show on their surfaces a distinct blending with the substance of the surrounding rock.[1] M. Renard has found that the Belgian whet-slate is full of minute crystals of garnet.[2] Yet the original truly sedimentary origin of clay-slate is indicated by its abundant clastic granules and flakes, by the traces of stratification, false-bedding, ripple-mark, &c., and by the occurrence of included organic remains. Some microscopic crystals may possibly have been originally formed among the muddy sediment on the sea-floor. But more probably they have been subsequently developed within the rock, and represent incipient stages of the process which has ended in the production of mica-schist and gneiss.[3] The development of crystals of chiastolite and other minerals in clay slate is frequently to be observed round bosses of granite as one of the phases of contact metamorphism.

A number of varieties of clay-slate are recognised. Roofing-slate (Dachschiefer) includes the finest, most compact, homogeneous and durable kinds, suitable for roofing houses or the manufacture of tables, chimney-pieces, writing-slates, &c.; it occurs in the Silurian and Devonian formations of Central and Western Europe. Whet-slate, novaculite, hone-stone, an exceedingly hard fine grained siliceous rock, some varieties of which derive their economic value from the presence of microscopic crystals. Chiastolite-slate (schiste maclé), a clay-slate in which crystals of chiastolite have been developed, even sometimes side by side with still distinctly preserved graptolites or other organic remains;[4] occurs at Skiddaw, also in Brittany, the Pyrenees, Saxony, Norway, Massachusetts, &c. Staurolite-slate, a micaceous clay-slate with crystals of staurolite; occurs in the Pyrenees. Ottrelite-slate a clay-slate marked by minute six-sided greyish or blackish green lamellæ of ottrelite; occurs in the Ardennes (where it is said to contain remains of trilobites), also in Bavaria and New England. Dipyre-slate is full of small crystals of dipyre. German petrographers have distinguished by name some other varieties characterised by different kinds of concretions, but to which no special designations have been given in English. *Knotenschiefer* contains little knots or concretions of a dark-green or brown fine granular, faintly glimmering substance, of a talcose or micaceous nature, imbedded in a finely laminated matrix of a talc-like or mica-like

[1] Zirkel, *Mik. Beschaff.* p. 490.
[2] *Acad. Roy. Belgique*, xli. (1877).
[3] Sorby, *loc. cit.* See Book IV. Part viii.
[4] A good illustration of this association is figured by Kjerulf in his *Geologie des Südlichen und Mittleren Norwegen*, Plate xiv. fig. 246.

mineral.[1] In *Fruchtschiefer* these concretions are like grains of corn; in *Garbenschiefer*, like caraway seeds; in *Fleckschiefer*, like flecks or spots. Some of these rocks might be included with the mica-schists.

Anthracitic-slate, Alum-slate, dark carbonaceous slate with much iron disulphide. Bands of this nature sometimes run through a clay-slate region. The carbonaceous material arises from the alteration of the remains of plants (fucoids) or animals (frequently graptolites). The marcasite so abundantly associated with these organisms decomposes on exposure, and the sulphuric acid produced, uniting with the alumina, potass, and other bases of the surrounding rocks, gives rise to an efflorescence of alum, or the decomposition produces sulphurous springs like those of Moffat.

Mica-schist (Mica-slate).—A schistose aggregate of quartz and mica, the relative proportions of the two minerals varying widely even in the same mass of rock. Each is arranged in lenticular wavy laminæ. The quartz shows greater inconstancy in the number and thickness of its folia. Frequently a layer of this mineral swells out to a thickness of an inch or more, and, dwindling rapidly down to a mere thread, disappears. The quartz often retains a granular character like that of quartz-rock, no doubt indicative of its original sedimentary origin. The mica lies in thin plates, sometimes so dovetailed into each other as to form long continuous irregular crumpled folia, separating the quartz layers, and often in the form of thin spangles and membranes running in the quartz. (Figs. 18 and 19). As the rock splits open along its micaceous folia, the quartz is not readily seen save in a cross fracture.

Muscovite is the usual mica in typical mica-schist; but it is sometimes replaced by biotite. In many lustrous schists which are now found to have a wide extent, the silvery foliated mineral is ascertained to be a hydrous mica (margarodite, damourite, &c.), and not talc, as was once supposed. These, as already stated, have been named hydro-mica-schists. Among the accessory minerals, garnet, schorl, felspar, hornblende, kyanite, staurolite, chlorite, and talc may be mentioned. Mica-schist readily passes into other members of the schistose family. By addition of felspar it merges into gneiss. By loss of quartz and increase of chlorite it passes into chlorite-schist, and by other gradations into quartz-rock, &c.

Mr. Sorby has pointed out that thin slices of true mica-schist when examined under the microscope show traces of the original grains of quartz-sand and other sedimentary particles of which the rock at first consisted. He has also found indications of current-bedding or ripple-drift, such as may be seen in many fine sedimentary deposits, and he concludes that mica-schist is merely a crystalline metamorphosed sedimentary rock.[2] Besides the original quartz-

[1] A. von Lasaulx, *Neues Jahrb. für Min.* (1872), p. 840. K. A. Lossen, *Z. Deutsch. Geol. Ges.* (1872), p. 757.

[2] *Q. J. Geol. Soc.* (1863), p. 401, and his recent address in vol. xxxvi. (1880), p. 85.

granules there has been a subsequent development of quartz, partly round these granules and partly in indefinite layers through the rock.

Among the varieties of mica-schist may be mentioned, Sericite-schist, composed of an aggregate of fine folia of the silky micaceous mineral sericite in a compact honestone-like quartz; Paragonite-schist where the mica is the hydrous soda variety, paragonite; Margarodite-schist where the mica is the hydrous form, margarodite.

Mica-schist, together with other schistose rocks, forms extensive regions in Norway, Scotland, the Alps, and other parts of Europe, and vast tracts of the Archæan regions of North America. It is also found encircling granite masses (Scotland, Ireland, &c.) as a metamorphic zone a mile or so broad, which shades away into unaltered greywacke or slate outside. In these cases it is unquestionably a metamorphosed condition of ordinary sedimentary strata, the change being connected with the extravasation of granite.

Though the possession of a fissile structure, showing abundant divisional surfaces covered with glistening mica, is characteristic of mica-schist, we must distinguish between this structure and that of many micaceous sandstones which can be split into thin seams each splendent with the sheen of its mica-flakes. A little examination will show that in the latter case the mica has not crystallized *in situ*, but exists merely in the form of detached worn scales, which, though lying on the same general plain, are not welded into each other as in a schist; also that the quartz does not exist in folia but in rounded separate grains.

Gneiss, a schistose aggregate of orthoclase (sometimes also oligoclase), quartz, and mica. It differs from granite chiefly in the foliated arrangement of the minerals. The quartz sometimes contains abundant liquid cavities, in which liquid carbon dioxide has been detected. The relative proportions of the minerals, and the manner in which they are grouped with each other, present great variations. As a rule, the folia are coarser and the schistose character less perfect than in mica-schist. Sometimes the quartz lies in tolerably pure bands a foot or even more in thickness, with plates of mica scattered through it. These quartz layers may be replaced by a crystalline mixture of quartz and felspar, or the felspar will take the form of independent lenticular folia, while the laminæ of mica which lie so abundantly in the rock, give it its fissile structure. Among the accessory minerals, garnet, tourmaline or schorl, hornblende, apatite, graphite, pyrites, and magnetite may be enumerated.

Many varieties of gneiss occur, some distinguished by peculiarities of structure, as where the rock is very fissile, or where it becomes granular or granitic; others by special minerals, as *mica-gneiss*,

which is the normal type; *hornblende-gneiss*, where hornblende takes the place of mica; *cordierite-gneiss*, with biotite and blueish cordierite; *protogine-gneiss*, where the mica is replaced by talc. Like mica-schist, gneiss occurs in vast bedded masses which occupy a large space in regions where the older geological formations come to the surface. Varieties of it are also found in the metamorphic zone encircling some masses of granite. So coarse is the texture of many gneisses that they cannot, in hand-specimens nor even in large blocks, be certainly discriminated from granite. In such cases it is only by examination in the field and the detection of clear evidence of a general foliated structure that their true character can be determined.

An interesting and important rock is met with in some regions of gneiss and schist, viz., a **schistose conglomerate**, in which pebbles of quartz and other materials from less than an inch to more than a foot in diameter are imbedded in a foliated matrix. Examples of this kind are found in the pass of the Tête Noire between Martigny and Chamouni, in north-west Ireland, in the islands of Bute, Islay, Garvelloch, and different parts of Argyllshire. The pebbles are not to be distinguished from the ordinary water-worn blocks of true conglomerates; but the original matrix which encloses them has been so altered as to acquire a micaceous foliated structure, and to wrap the pebbles round as with a kind of glaze. These facts, like those already referred to in the microscopic structure of mica-schist, are of considerable value in regard to the theory of the origin of the crystalline schists.

Granulite (Leptynite, Eurite schistoide, Weiss-stein).[1]—A schistose aggregate, consisting mainly of orthoclase and quartz, with red garnet and some kyanite; is by some petrographers classed as an eruptive rock with the granites. It occurs in well-defined foliated beds associated with gneiss and other crystalline rocks in Saxony, where several varieties of the rock have been observed, one of which consists of diallage, triclinic felspar, quartz, garnet, and biotite.

A few other crystalline rocks, found in comparatively small quantity, associated with the crystalline schists, may be mentioned here.—Garnet-rock, a crystalline-granular aggregate of garnet, hornblende, and magnetite; kyanite-rock, a mixture of blue kyanite, red garnet, green smaragdite, and silver-white mica; eclogite (omphacite-rock), composed of grass-green smaragdite and red garnet; kinzigite, of mica, garnet, and a triclinic felspar.

The chemical composition of some normal varieties of schistose rocks is here appended; but the proportions of the constituents vary considerably in different examples of the same rock.

[1] Michel-Lévy, &c., *Bull. Soc. Géol. France*, 3rd ser. ii. pp. 177, 189, iii. p. 287, iv. p. 730, viii. p. 14. Scheerer, *Neues Jahrb.* 1873, p. 673. Dathe, *Z. Deutsch. Geol. Ges.* 1877, p. 274. Details will be found in the explanatory pamphlets published with the sheets of the Geological Survey of Saxony, especially those of sections Rochlitz, Geringswalde, and Waldheim.

	Spec. Grav.	Silica.	Alumina.	Iron, perox.	Iron, protox.	Mangan, protox.	Lime.	Magnesia.	Potash.	Soda.	Water.
Talc-schist . .	..	50—58	4·5—9·0	3·5—7·0	1·0	..	1·0—1·5	23·0—31·5	..	..	0—6
Chlorite-schist .	2·7—2·9	42—55	3—14	0—4·5	9—27	0·5	0·2—1·5	8—17	0·6	0·2—1·5	4·5—11·2
Hornblende-schist	3·0—3·1	48—50	13·3—16·4	12—27·5	4·5—9	0—0·5	0·6—12	2—2·6	0·5—1·2	1·9—2·3	..
Hornblende-rock .	2·94	49·42	18·12	5·41	9·60	..	8·65	3·16	1·27	2·57	1·80 loss
Clay slate . . .	2·6—2·9	54—64	13—23	0—19	0—8·5	..	0·5—9	1—9·5	1—6	0·1—3·9	0—3·9
" alum slate .	2·42	52·28	16·64	FeS_2 7·74	6·96	..	1·53	1·10	7·98	(carbon) 4·37	1·40 loss
Mica-schist . .	2·77	65·13	18·16	..	5·27	0·51	0·32	2·70	2·99	0·53	TiO_2 1·54
Mica-gneiss . .	2·70	65—75	13—21	0—5·8	0—6	0—0·5	1—5	0·5—3·0	1·5—4·8	0·5—2·5	..
Hornblende-gneiss	2·80	56·83	19·68	2·88	5·76	trace.	1·89	3·28	3·14	2·34	{TiO_2 0·47 {CuO 0·09
Granulite . . .	2·66	73·47	14·86	..	3·28	..	1·62	0·67	3·95	1·80	H_2O, 0·57

Quartz-rock, Quartzite, though not properly a schistose rock, may be most conveniently considered here, as it is so constant an accompaniment of the schists, and, like them, can often be directly traced to the alteration of former sedimentary formations. It is a granular to compact mass of quartz, generally white, sometimes yellow or red, with a characteristic lustrous fracture. It occurs in thin and thick beds in association with schists, sometimes in continuous masses several thousand feet thick. In Scotland it forms ranges of mountains, and is there frequently accompanied with subordinate beds of limestone, which in Sutherlandshire contain Lower Silurian fossils.

Even to the naked eye, the finely granular or arenaceous structure of quartz-rock is distinctly visible. Microscopic examination shows this structure still more clearly, and leaves no doubt that the rock originally consisted of a tolerably pure quartz-sand, which has been metamorphosed by pressure and the transfusion of a siliceous cement

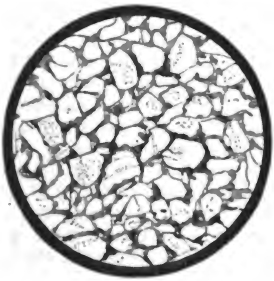

FIG. 20.—MICROSCOPIC STRUCTURE OF QUARTZ-ROCK.

into an exceedingly hard mass. This cement was probably produced by the solvent action of heated water upon the quartz grains, which seem to shade off into each other, or into the intervening silica. It is owing, no doubt, to the purely siliceous character of the grains that the blending of these with the surrounding cement is so intimate, that the rock often assumes an almost flinty homogeneous texture. That quartzite as here described is an original sedimentary rock, and not a chemical deposit, is shown not only by its granular texture, but by the exact resemblance of all its leading features to ordinary sandstone—false-bedding, alternation of coarser and finer layers, worm-burrows, and fucoid-casts. The lustrous fracture which distinguishes this rock from sandstone is due to the exceedingly firm cohesion of the component grains which break across rather than separate, and to the consequent production of innumerable minute clear vitreous surfaces of quartz. A sandstone, on the other hand, has its grains so loosely coherent, that when the

rock is broken the fracture passes between them, and the new surface obtained presents innumerable dull rounded grains.

Besides occurring in alternation with schists, quartzite is also met with locally as an altered form of sandstone, which when traversed by igneous dykes is indurated for a distance of a few inches or feet from the intrusive mass. These local productions of quartzite show the characteristic lustrous fracture, and have not yet been distinguished by the microscope from the quartz-rock of wide metamorphic regions. There is yet another condition under which this rock or one of analogous structure may be seen. Highly silicated bands, having lustrous aspect, fine grain, and great hardness, occur among the unaltered shales and other strata of the Carboniferous system. In such cases, the supposition of any general metamorphism being inadmissible, we may infer either that these quartzose bands have been indurated, for example, by the passage through them of thermal silicated water, or that they are an original formation.

Schistose Quartzite (Quartz-schist).—The gradation from quartz-rock into the various schists can be traced in almost any region of metamorphic rocks. It is perfectly analogous to the passage of sandstone into shales and other sedimentary formations. The Highlands of Scotland consist in large measure of rocks which are not properly either mica-schist or ordinary quartz-rock. Consisting of granular quartz, with abundant parallel laminæ of mica, and capable of being split into thick or thin flagstones, they may be called quartz-schists. They were evidently at first sandstones, with interleaved seams of fine mud. The sand has been converted into quartzite, and the argillaceous layers have passed into various micaceous minerals. Endless varieties in the relative proportions of these ingredients may be observed.

Itacolumite.—A schistose quartzite, in which the quartz-granules are separated by fine scales of mica, talc, chlorite, and sericite. Occasionally these pliable scales are so arranged as to give a certain flexibility to the stone (flexible sandstone). This rock occurs in the south-eastern states of North America, also in Brazil, as the matrix in which diamonds are found.

Hälleflinta (Helleflinta).—An exceedingly compact felsitic grey, yellowish, greenish, brownish, or black rock, composed of an intimate mixture of microscopic particles of felspar and quartz, with fine scales of mica and chlorite. It breaks with a splintery or conchoidal fracture, presents under the microscope a finely-crystalline structure, and is only fusible in fine splinters before the blow-pipe. Though externally presenting a resemblance to felsite, one of the massive rocks, it occurs in beds so intimately associated with the gneisses of Norway, that it has probably been produced by the same series of changes that gave rise to the crystalline schists.

Porphyroid.—A name bestowed upon certain rocks composed of a felsite-like ground-mass which has assumed a more or less schistose

structure from the development of micaceous scales, and which contains porphyritically scattered crystals of felspar and quartz. The felspar is either orthoclase or albite, and may be obtained in tolerably perfect crystals. The quartz occasionally presents doubly terminated pyramids. The micaceous mineral may be paragonite or sericite. Porphyroid occurs among the schistose rocks of Saxony,[1] in the palæozoic area of the Ardennes,[2] as well as in Westphalia and other parts of Europe.

Before passing from the schistose series of rocks, the student will observe that the disappearance of the schistose structure produces a crystalline amorphous compound. In gneiss, for example, the same minerals which form granite have crystallized in a foliated manner. Any process, such as irregular internal motion of the mass that could change the schistose structure of gneiss into the massive structure of granite, would give rise to a rock which, whatever its previous history might have been, might not be distinguishable from granite. On the other hand, any internal rearrangement which could produce a foliated structure within a mass of granite, would present a rock that would deserve the name of gneiss. That such internal transformations have taken place among the crystalline schists and some granites and other eruptive rocks can hardly be doubted. And thus, at the one end of the schistose series, we find rocks in which an original sedimentary character remains unmistakable; while at the other, after many intermediate stages of progressively augmenting crystallization, we encounter thoroughly crystalline amorphous masses like granite and syenite, which should be placed among the massive rocks. This arrangement no doubt correctly represents what has been a real cycle of alteration among rocks. Sedimentary deposits have been gradually changed and crystallized. These metamorphosed products, by upheaval and exposure at the surface, have again been reduced to sediment, perhaps once more to pass through the same succession of alterations and to become yet again crystalline.

3. Massive Rocks.

This important sub-division is nearly coincident with what is embraced by the old and useful terms Igneous or Eruptive Rocks. Almost the whole of its members have been produced from within the crust of the earth, in a molten or at least in a pasty condition. Nearly all consist of two or more minerals. Considered from a chemical point of view, they may be described as mixtures in different proportions of silicates of alumina, magnesia, lime, potash, and soda, usually with magnetic iron and phospate of lime. In one series the silicic acid has not been more than enough to combine with the different bases; in another it occurs in excess as free quartz. Taking this feature as a basis of arrangement, some

[1] Rothpletz, *Geol. Survey Saxony.* Explanation of Section Rochlitz.
[2] De la Vallée Poussin and Renard, *Mem. Couronnées Acad. Roy. Belg.* 1876, p. 85.

petrographers have proposed to divide the rocks into an acid group, including such rocks as granite, quartz-porphyry and quartz-trachyte, where the percentage of silica ranges from 60 to 75 or more, and a basic group, typified by such rocks as leucite-lava and basalt, where the proportion of silica is only about 50 per cent.

In the vast majority of igneous rocks the chief silicate is a felspar—the number of rocks where the felspar is represented by another silicate (as leucite or nepheline) being comparatively few and unimportant. As the felspars group themselves into two divisions, the monoclinic or orthoclase, and the triclinic or plagioclase, the former with, on the whole, a preponderance of silica; and as these minerals occur under tolerably distinct and definite conditions, it is customary to divide the felspar-bearing massive rocks into two series,—(1) the orthoclase rocks, having orthoclase as their chief silicate, and often with free silica in excess, and (2) the plagioclase rocks, where the chief silicate is some species of triclinic felspar. The former series corresponds generally to the acid group above mentioned, while the plagioclase rocks are on the whole decidedly basic. It has been objected to this arrangement that the so-called plagioclase felspars are in reality very distinct minerals, with proportions of silica, ranging from 43 to 69 per cent.; soda from 0 to 12; and lime from 0 to 20.[1] But the state of minute subdivision in which the minerals occur in most massive rocks, makes the determination of the species of felspar so difficult that the term plagioclase is of great service as at least a provisional term under which to unite the felspars that crystallize in triclinic forms. In addition to the felspar-rocks, there must be noted those in which felspar is either wholly absent or sparingly present, and where the chief part in rock-making has been taken by nepheline, leucite, olivine, or serpentine.

From the point of view of internal structure a classification based upon microscopic research has recently been proposed by MM. Fouqué and Michel-Lévy. These writers, pointing out that most eruptive rocks are the result of successive stages of crystallization each recognizable by its own characters, affirm that two phases of consolidation are specially to be observed, the first marked by the formation of large crystals which were often broken and corroded by mechanical and chemical action within the still unsolidified magma; the second by the formation of smaller crystals, crystallites, &c., which are moulded round the older series. In some rocks the former, in others the latter of these two phases is alone present. Two leading types of structure are recognized among the eruptive rocks. 1. Granitoid, where the constituents are mainly those of the second epoch of consolidation, but where neither amorphous magma, nor crystallites are to be seen. This structure includes three varieties, (*a*) the *granitoid* proper, having crystals of ap-

[1] Dana, *Amer. Jour. Sci.* 1878, p. 432. This article contains a trenchant criticism of modern lithological classification. See on the subject of the retention of the term "plagioclase," Bonney, *Geol. Mag.* 1879, p. 200.

proximately equal size; (*b*) *pegmatoid*, where there has been a simultaneous crystallization and regular arrangement of two constituents; (*c*) *ophitic*, in which the felspars are ranged parallel to one of their crystalline faces, forming a kind of transition into microlithic rocks. 2. Trachytoid, distinguished by a more marked contrast between the crystals of the first and second consolidation, the usual presence of an amorphous magma, and the fluxion structure. Three types are named, (*a*) *petrosiliceous*, with trains and spherulites of a finely clouded substance characteristic of the more acid rocks; (*b*) *microlithic*, characterised by the abundance of microliths of felspars and other minerals; (*c*) *vitreous*, derived from the two foregoing types by the predominance of the amorphous paste.[1]

(1.) Felspar-bearing Series.

a. Orthoclase Rocks.

a. Quartziferous.

In this family the silicic acid has been in such excess as to separate out abundantly in the form of free quartz. Sometimes, as in granite, it has not assumed a definitely crystallized form, but is moulded round the other crystals as a later stage of consolidation. In other rocks (quartz-porphyry, &c.) it occurs as a product of earlier consolidation. It often assumes perfect crystallographic contours, occurring even in double pyramids. The texture of the rocks is (1) crystalline-granular (granitoid) as typically developed in granite; (2) porphyritic (trachytoid), as in quartz-porphyry or felsite; (3) vitreous, as in pitchstone.

Granite.[2]—A thoroughly crystalline-granular admixture of felspar, mica, and quartz in particles of tolerably uniform size. The felspar is chiefly white or pink orthoclase, but triclinic felspars (oligoclase and albite) may often be observed in smaller quantity, frequently distinguishable by their fine striation and more waxy lustre. The mica may be either the potash or muscovite variety, usually of a white silvery aspect; or may belong to biotite (magnesian mica) or lepidomelane, when it is commonly dark brown or black. Dr. Heddle finds the common mica of the granites in the Scottish Highlands to be a new variety, which he has called haughtonite. The quartz may be observed to form a kind of paste or magma wrapping round the other ingredients. Only in cavities of the granite do the component minerals occur in independent well-formed crystals, and there too the accessory minerals (beryl, topaz, tourmaline, &c.) are chiefly found.

From a microscopic examination of granite it was formerly in-

[1] *Op. cit.* p. 150.

[2] On the structure of granite see the manuals of Zirkel and Rosenbusch and the memoirs there cited; also Zirkel's *Microscop. Petrography*, 1876, p. 39; Phillips, *Q. J. Geol. Soc.* xxxi. p. 330; xxxvi. p. 1. J. C. Ward, *op. cit.* p. 569, and xxxii. p. 1. King's *Systematic Geology* (vol. i. of *Explor. 40th Parallel*), p. 111, *et seq.* Michel-Lévy, *Bull. Soc. Géol. France*, 3rd ser. iii. p. 199.

ferred that the rock has a thoroughly crystalline structure, with no macroscopic ground-mass, nor microscopic base of any kind between the crystals or crystalline individuals. More recent and exhaustive study of the subject, however, has led to the conclusion that though nothing like a vitreous or even porphyritic ground-mass can be detected, there is yet discernible an analogous kind of entirely crystalline magma, in which the crystals or crystalline débris of the rock are embedded, and in which they are partially dissolved. Having regard to the relations between this magma and its enclosed minerals, M. Michel-Lévy has observed that microscopic examination points to a distinction between granites in which the quartz is more recent than the other constituents and has consolidated at once, and those in which there are remains of earlier bi-pyramidal quartz. He distinguishes these two series as (A) Ancient granites, composed of black mica, hornblende, oligoclase, and orthoclase, forming a crystalline débris embedded in a more recent crystalline magma of orthoclase and quartz. (B) Porphyroid granites, generally finer in grain than the preceding, and further distinguished by the occurrence of bi-pyramidal crystals of quartz (which made their appearance between the old felspar and the recent orthoclase), and of a notable quantity of white mica (rare among the ancient granites) posterior in advent even to the more recent quartz.[1]

Among the component minerals of granite, the quartz presents special interest under the microscope. It is often found to be full of cavities containing liquid, sometimes in such numbers as to amount to a thousand millions in a cubic inch. The liquid in these cavities appears usually to be water containing sodium and potassium chlorides, with sulphates of these metals and of calcium (p. 96).

The mean of eleven analyses of granites made by Dr. Haughton gave the following average composition: silica, 72·07; alumina, 14·81; peroxide of iron, 2·22; potash, 5·11; soda, 2·79; lime, 1·63; magnesia, 0·33; loss by ignition, 1·09; total, 100·05, with a mean specific gravity of 2·66.

Most large masses of granite present differences of texture in different parts of their area. In particular they are apt to be traversed by veins, sometimes due to a segregation of the surrounding minerals in rents of the original pasty magma, sometimes to a protrusion of a less coarsely crystalline (felsitic) part of the granitic mass into fissures of the main rock (Fig. 21). Some of the more important of these varieties are distinguished by special names. Thus, where the component minerals assume large proportions, as they are specially apt to do in segregation veins, the rock is termed *Pegmatite*, the quartz and felspar having crystallized together in masses often larger than a man's head, the mica also assuming the shape of plates several inches or even feet in diameter. Such coarse-grained varieties may be found here and there in venous or cavernous spaces in the heart of

[1] *Bull. Soc. Géol. France*, 3rd ser. iii. (1875) p. 199.

many ordinary granites. Here and there an example may be found of a granite becoming fine-grained but containing large scattered felspar crystals. Such a rock may be termed a *porphyritic granite*, or, if the ground mass be finely crystalline and tolerably uniform in texture, *Granite-porphyry*.[1] One of the most interesting structural

FIG. 21.—VEIN OF FINER GRAIN TRAVERSING A COARSELY CRYSTALLINE GRANITE.

varieties is that termed *graphic granite*. It is distinguished by the manner in which the quartz has assumed the shape of long imperfect columnar shells, placed parallel to each other and enclosed within the orthoclase, so that a transverse section bears some resemblance to Hebrew writing. The two minerals have crystallised together and this has taken place in veins. The parallelism of the quartz shells seems to show that there could have been little or no internal movement of these veins when the component minerals assumed their crystalline forms. Some granites abound in enclosed crystalline concretions or fragments. These are sometimes mere segregations of the materials of the granite, when they are usually ovoid in form and porphyritic in structure; in other cases they are fragments of other rocks, and are then commonly schistose in structure and irregular in form.[2] In the centre as well as round the edges of large bosses of granite the minerals occasionally assume a more or less

[1] On granite porphyry see Zirkel, *Microscop. Petrog.* p. 60. Kalkowsky, *Neues Jahrb.* 1878, p. 276. [2] J. A. Phillips, *Q. J. Geol. Soc.* xxxvi. p. 1.

perfectly schistose arrangement. When this takes place, the rock is called "gneissose" or gneiss-granite. (See Book IV. Part vii.)

Differences in the proportions or nature of the component minerals have likewise suggested distinctive names. Of these the following are the more important: *Granitite,*—a mixture of pink orthoclase and abundant oligoclase with a little quartz and some blackish green magnesia-mica; *Protogine,*—consisting of orthoclase, oligoclase, hexagonal tables of a dark green mica, and pale green talc, occurs among the crystalline rocks of the Alps; *Syenite-granite,* —a rock in which hornblende is added to the other normal constituents of granite, is usually poorer in quartz than normal granite. It derives its name from Syene in Upper Egypt, whence it was obtained anciently in large blocks for obelisks and other architectural works. The well-known Egyptian monoliths are made of it. Syenite-granite is found in the Vosges, at Pilson in Bohemia, in the Pyrenees, and in different parts of Scotland, notably in masses of tertiary age which have invaded and altered the Lias rocks of Skye and Raasay. It there sometimes assumes a porphyry-structure. *Granulite* is by some authors included among the granites (p. 125).

Surrounding large masses of granite there are usually numerous veins which consist sometimes of granite and sometimes of varieties of quartz-porphyry. There can be no doubt that these porphyritic protrusions really proceed from the crystalline granite mass. Lossen has shown that the Bode vein in the Harz has a granitoid centre with compact porphyry sides, in which he found with the microscope a true glassy base.[1] Sometimes the rocks associated in this way with granite differ in composition from the main granite. Thus *greisen* is a granular aggregate of quartz and mica (usually lepidolite) which by addition of felspar passes into granite; *Tourmaline-rock* or *schorl-rock,* is a crystalline aggregate of quartz and black tourmaline or schorl.

Granite weathers chiefly by the decay of its felspars. These are converted into kaolin, the mica becomes yellow and soft, while the quartz stands out scarcely affected. The granite of the south-west of England weathers to a depth of twenty feet or more, so that it can be dug out with a spade.

Granite occurs (1) as an eruptive rock, forming huge bosses, which rise through other formations both stratified and unstratified, and sending out veins into the surrounding and overlying rocks, which usually show evidence of much alteration as they approach the granite; (2) connected with true volcanic rocks (as in the case in Skye just cited) and forming, perhaps, the lower portions of masses which flowed out at the surface as lavas; and (3) in the heart of mountain chains and elsewhere, interbedded with gneiss and other metamorphic rocks in such a manner as to suggest that it is itself a final stage of metamorphism. Granite is thus a decidedly *plutonic* rock; that is, it has consolidated at some depth beneath the surface,

[1] *Z. Deutsch. Geol. Ges.* xxvi. (1874) p. 856.

and in this respect differs from the superficial *volcanic* rocks, such as lavas, which have flowed out above ground from volcanic orifices.

Quartz-Porphyry (Quartz-felsite).[1]—Under this title are included several varieties of rock which agree in consisting fundamentally of a very fine grained felsitic ground-mass, composed mainly of orthoclase and quartz. Where these minerals are crystallized in conspicuous forms the rock is a *quartz-porphyry* (*felsite-porphyry, eurite*); where the whole mass is more homogeneous and flinty in texture it is a *felsite* or *felstone*.

Quartz-porphyry is composed of a compact ground-mass through which are dispersed crystals or crystalline blebs of quartz and crystals of orthoclase, sometimes of a triclinic felspar, mica or hornblende. Though to the eye in fresh specimens the ground-mass often appears homogeneous and almost flinty in texture, it generally presents under the microscope the microfelsitic structure already described (p. 104). Sometimes the base is found to be distinctly glassy, while in other cases it appears partly glassy and partly microfelsitic. Occasionally it assumes a more crystalline character, even sometimes recalling the structure of a fine grained granite. Beautiful examples of spherulitic structure are occasionally to be observed where minute spherical concretions occur with an internal fibrous radiating structure. Fluxion-structure is well developed among some of the quartz-porphyries associated with the metamorphic rocks of the north-east of Scotland.

The quartz occurs in imperfect occasionally corroded crystals or blebs, but sometimes in perfect doubly-terminated pyramids, varying in size from minute forms only discernible with the microscope, up to crystals as large as a bean. It abounds with liquid inclusions. The orthoclase takes the form of more or less complete crystals, not seldom twinned; the contour which its cross sections present to the eye, depending upon the angle at which the individual crystals are bisected. It is chiefly the dispersed orthoclase which gives the distinctively porphyritic aspect to the rock. Triclinic felspar (believed to be usually oligoclase) also takes a place, distinguishable when fresh, by its fine lineation, but apt to become dull and kaolinized by weathering. Mica and hornblende are among the most common of the minerals which accompany the two essential constituents, while apatite, magnetite, and pyrite are not infrequent accessories.

The flesh-red quartz-porphyry of Dobritz, near Meissen, in Saxony, was found by Rentzsch to have the following chemical composition:—Silica, 76·92; alumina, 12·89; potash, 4·27; soda, 0·68; lime, 0·68; magnesia, 0·98; oxide of iron, 1·15; water, 1·97; total, 99·54,—specific gravity, 2·49.

The colours of quartz-porphyry depend chiefly upon those of the felspar,—flesh-red, reddish-brown, purple, yellow, bluish or slate-grey, and even white, being in different places characteristic. The presence of much mica or hornblende gives dark grey, brown, or

[1] Zirkel, *Microscop. Petrog.* p. 71. See particularly Rosenbusch, *Mik. Phys.* ii. p. 50.

greenish tints. It will be observed in this, as in other rocks containing much felspar, that the colour, besides depending on the hue of that mineral, is greatly regulated by the nature and stage of decomposition. A rock weathering externally with a pale yellow or white crust may be found to be quite dark in the central undecayed portion. Besides these differences of aspect arising from varieties of colour, ground-mass, &c., distinctions are to be observed according to the relative abundance and size of the felspar crystals, and the presence of mica (*micaceous quartz-porphyry*), hornblende (*hornblendic quartz-porphyry*), or other accessory ingredient. When the base is very compact, and the felspar-crystals well defined and of a different colour from the base, the rock sometimes takes a good polish, and may be used with effect as an ornamental stone. In popular language such a stone is classed with the "marbles," under the name of "porphyry."

Closely related to the quartz-porphyries, of which, indeed, it can be regarded only as a variety, comes the rock known as *elvan* or *elvanite*. This is a Cornish term for a crystalline-granular mixture of quartz and orthoclase, forming veins which proceed from granite, or occur only in its neighbourhood, and are evidently associated with it. It forms an intermediate stage between granite and quartz-porphyry.[1]

Felsite (Felstone, Petrosilex), a hard and excessively compact flinty-like rock, composed of an intimate mixture of quartz and orthoclase. The ground-mass presents under the microscope a structure like that of quartz-porphyry, into which felsite naturally passes by the appearance of the porphyritic minerals.

The quartz-porphyries and felsites occur (1) with plutonic rocks, as eruptive bosses or veins, often associated with granite, from which, indeed, as above stated, they may be seen to proceed directly; of frequent occurrence also as veins and irregularly intruded masses among highly convoluted rocks, especially when these have been more or less metamorphosed; (2) in the chimneys of old volcanic orifices, forming there the "neck" or plug by which a vent is filled up; and (3) as truly volcanic rocks which have been erupted at the surface in the form of flows of lava, either (*a*) submarine, as in the felstones of Wales,[2] or (*b*) subaerial, as probably in the quartz-porphyry of Arran, and perhaps in the series of "green-slates and porphyries" of the Silurian system in Cumberland,[3] which Professor Ramsay has conjectured to be the products of a subaerial volcano. These eruptive rocks are abundant in Britain among formations of Lower Silurian, Old Red Sandstone and Lower Carboniferous age. In the Inner Hebrides they overlie and alter the Jurassic

[1] J. A. Phillips, *Q. J. Geol. Soc.* xxxi. p. 334. Michel-Lévy, *Bull. Soc. Géol. France*, iii. 3rd ser. p. 201.

[2] J. C. Ward, *Q. J. Geol. Soc.* xxxi. p. 399. The felsite of Aran Mowddwy contains 83·8 per cent. of silica.

[3] J. C. Ward, *op. cit.* p. 400.

rocks. They were poured out on a great scale during Permian and early Triassic times in Westphalia and the Thuringer Wald.

Liparite—(Rhyolite, Quartz-trachyte), a rock composed of a compact or fine-grained ground-mass containing crystals of sanidine and quartz, often with black mica and hornblende, triclinic felspar, augite, apatite, and magnetite. Considerable diversity exists in the texture of this rock. Some varieties are coarse and granitoid in character. Intermediate varieties may be obtained like the quartz-porphyries, passing by degrees into more or less distinctly vitreous rocks. Throughout these gradations, however, which may represent different stages in the crystallization of an original molten glass, a characteristic ground-mass can be seen under the microscope having a glassy, enamel-like, porcellanous, microfelsitic, or sometimes even a finely granitic character. An analysis by Vom Rath of a rhyolite from the Euganean Hills gave—silica, 76·03; alumina, 13·32; soda, 5·29; potash, 3·83; protoxide of iron, 1·74; magnesia, 0·30; lime, 0·85; loss, 0·32; total, 101·68,—specific gravity, 2·553.

Liparite is an acid rock of volcanic origin, and late geological date which in more recent times has played a part similar to that of the granitic and felsitic rocks of older periods, though it has not been yet observed as a product of any still active volcano. It forms enormous masses in the heart of extinct volcanic districts in Europe (Hungary, Euganean Hills, Iceland, Lipari) and in North America (Wyoming, Utah, Idaho, Oregon, California).[1]

Among the rocks above enumerated a distinct gradation can sometimes be traced from a thoroughly crystalline granitoid structure into a porphyritic mass with the characteristic ground-mass. Among the porphyritic varieties also traces can be detected of a vitreous base indicative of the rocks having once existed as glass. The vitreous compounds are placed together at the end of the non-quartziferous group (pp. 140–142).

β. Quartzless, or poor in Quartz.

In this group free quartz is not found as a marked constituent, although occasionally it occurs in some quantity, as microscopic examination has shown in the case even of some rocks where the mineral was formerly believed to be absent. A range of structure is displayed similar to that of the quartziferous series. The thoroughly crystalline varieties are typified by syenite, which represents the granites of the quartziferous rocks, those which possess a porphyritic ground-mass by orthoclase porphyry and trachyte, answering to quartz-porphyry and liparite.

Syenite.—This name, formerly given in England to a granite with hornblende replacing mica, is now restricted to a rock consisting essentially of a crystalline-granular mixture of orthoclase and

[1] On liparite or rhyolite see Zirkel, *Micro. Petrog.* p. 163. King, *Explor. 40th Parallel*, p. 606.

hornblende, to which plagioclase, quartz, and mica are occasionally added. The word, first used by Pliny in reference to the rock of Syene, was introduced by Werner as a scientific designation, and applied to the rock of the Plauenscher-Grund, Dresden. Werner afterwards, however, made that rock a greenstone. The base of all syenites like that of granites is thoroughly crystalline, without an amorphous ground-mass.

The typical syenite of the Plauenscher-Grund, formerly described as a coarse-grained mixture of flesh-coloured orthoclase and black hornblende, containing no quartz, and with no indication of plagioclase, was regarded as a normal orthoclase-hornblende rock. Microscopical research has, however, shown that well-striated triclinic felspar, as well as quartz, occur in it. Its composition is:—silica, 59·83; alumina, 16·85; protoxide of iron, 7·01; lime, 4·43; magnesia, 2·61; potash, 6·57; soda, 2·44; water, &c., 1·29; total, 101·03. Average specific gravity 2·75 to 2·90.

Among the accessory minerals of common occurrence may be mentioned titanite (sphene), quartz, apatite, epidote, orthite, magnetite, pyrite, zircon. The predominance of one or more of these ingredients has given rise to the separation of a few varieties under distinctive names. *Zircon-syenite,* the characteristic rock of Laurvig in Southern Norway, consists of orthoclase, zircon, hornblende, and the ancient form of nepheline termed elæolite. When mica occurs in abundance the rock is termed *mica-syenite.* Sometimes augite in crystals or crystalline granules makes its appearance and forms *augite-syenite.* The name *foyaite* (from Mount Foya in the Portuguese province of Algarve), *miascite* (from Miask), *ditroite* (from Ditro in Transylvania), are syenitic rocks containing elæolite and other minerals.

Syenite occurs of many different ages from early Palæozoic up to Miocene, under conditions similar to those in which granite is found; it has been erupted in large irregular masses, especially among metamorphic rocks, as well as in smaller bosses and veins. It is likewise sometimes associated with syenitic granite, quartz-porphyry, and other orthoclase rocks at the roots of volcanic hills, as in Raasay and Skye in the West of Scotland, where it has overflowed Jurassic rocks, and is itself of Miocene age.

Orthoclase-Porphyry (*Quartzless-porphyry*) stands to the syenites in the same relation that quartz-porphyry does to the granites. It is composed of a compact porphyritic ground-mass with little or no free quartz, but through which are usually scattered numerous crystals of orthoclase, sometimes also a triclinic felspar, black hornblende and glancing scales of dark biotite. It contains from 55 to 65 per cent. of silica, thus differing from quartz-porphyry and felsite in its smaller proportion of this acid, but the distinction is one which, except by chemical or microscopical analysis, must often be difficult to establish between the fine compact felsites and the orthoclase porphyries, especially when the latter (as the microscope shows) contain

free quartz. This rock is sometimes termed syenite-porphyry, since it is associated with syenite much in the same way that elvanite is with granite. But this name should be retained for the finely crystalline varieties, which would thus represent among the quartzless orthoclase rocks granite-porphyry in the quartziferous series. The term Minette (Mica-trap) is applied to a variety which contains abundant scales of mica. Orthoclase-porphyry occurs in veins, dykes, and intrusive sheets. Probably many so-called felstones, whether occurring as lavas or as intrusive masses, among the older Palæozoic formations are really orthoclase-porphyries.

The orthoclase-porphyry of Pieve in the Vicentin was found by Von Lasaulx to have the following composition. Silica, 61·07; alumina, 18·56; peroxides of iron and manganese, 2·60; potash, 6·83; soda, 3·18; lime, 2·86; magnesia, 1·08; carbonic acid, 1·36; loss, 2·13—specific gravity, 2·59.[1]

Orthoclase-porphyry is largely developed among the later Palæozoic formations of Thuringia, the Harz, and Saxony, where it occurs both intrusively in dykes, and intercalated in large beds.

Trachyte.[2]—A term originally applied to modern volcanic rocks possessing a characteristic roughness (τραχύς) under the finger, is now restricted to a rock consisting essentially of sanidine, with more or less triclinic felspar, usually with hornblende, biotite, and magnetite, and sometimes with augite, apatite, and tridymite. It is thus distinguished macroscopically from liparite or quartz-trachyte by the absence of quartz. Microscopically it is to be discriminated from that rock by the absence or feeble development of the microfelsitic substance so abundant in liparite, and by the preponderating aggregate which it presents of minute colourless felspar-microliths with usually needles and granules of greenish hornblende and much diffused magnetite dust. The average composition of trachyte may be stated thus:—silica, 60·0—64·0; alumina, 17·0; protoxide and peroxide of iron, 6·0—8·0; magnesia, 1·0; lime, ·3·5; soda, 4·0; potash, 2·0—2·5. Average specific gravity, 2·65.

Trachyte is an abundantly diffused lava of Tertiary and Post-tertiary date. It occurs in most of the volcanic districts of Europe (Siebengebirge, Nassau, Transylvania, Bay of Naples, Euganean Hills.) It has been poured out upon a vast scale in the western territories of the United States. It occurs also in New Zealand.

Phonolite (clinkstone).[3]—A term suggested by the metallic ringing sound emitted by the fresh compact varieties when struck, is applied to a compact grey or brown quartzless mixture of sanidine and nepheline with hornblende and usually nosean. Under the microscope the ground-mass is not vitreous or half devitrified, but

[1] *Z. Deutsch. Geol. Ges.* xxv. p. 320. On "mica-traps" see Bonney, *Q. J. Geol. Soc.* xxxv. p. 165.

[2] On trachyte see Zirkel, *Micro. Petrog.* p. 143. King in vol. i. of *Explor. 40th Parallel*, p. 578.

[3] Boricky, "Petrograph. Stud. Phonolitgestein. Böhmens"—*Archiv. Landesdurchforschung Böhmen.* 1874.

appears as a crystalline aggregate of plates of sanidine and hexagonal prisms of nepheline with less frequent crystals of leucite, hornblende, augite, magnetite and hauyne. The rock is rather subject to decomposition, hence its fissures and cavities are frequently filled with zeolites. An average specimen contains silica, 57·7; alumina, 20·6; potash, 6·0; soda, 7·0; lime, 1·5; magnesia, 0·5; oxides of iron and manganese, 3·5; loss by ignition, 3·2 per cent. The specific gravity may be taken as about 2·58. Phonolite is sometimes found splitting into thin slabs which can be used for roofing purposes. Occasionally it assumes a porphyritic texture from the presence of large crystals of sanidine or of hornblende. When the rock is partly decomposed and takes a somewhat porous texture, it resembles trachyte in appearance.

Like trachyte, phonolite is a thoroughly volcanic rock and of Tertiary date. It occurs sometimes filling the pipes of volcanic orifices, sometimes as sheets which have been poured out in the form of lava-streams, and sometimes in dykes and veins, as in Bohemia and Auvergne.

Pitchstone (Retinite)—A vitreous, pitch-like rock easily frangible, translucent on thin edges, having usually a black or dark-green colour that ranges through shades of green, brown, and yellow to nearly white. It is essentially an orthoclase rock, and may be regarded as the natural glass resulting from the rapid cooling of many of the more granular or crystalline orthoclase rocks, such as the quartz-porphyries or felsites. Examined microscopically, it is found to consist of glass in which are diffused, in greater or less abundance, hair-like microliths, angular or irregular grains, or more definitely formed crystals of orthoclase, plagioclase, quartz, &c. The pitchstone of Corriegills, in the island of Arran, presents abundant green, feathery, and dendritic microliths of a pyroxenic character (Fig. 9). Occasionally, as in Arran, pitchstone assumes a spherulitic or perlitic structure. Sometimes it becomes porphyritic by the development of abundant sanidine crystals (Isle of Eigg).

According to Durocher the mean composition of pitchstone is—silica, 70·6; alumina, 15·0; potash, 1·6; soda, 2·4; lime, 1·2; magnesia, 0·6; oxides of iron and manganese, 2·6; loss by ignition, 6·0. Mean specific gravity 2·34.

Pitchstone is found as (1) intrusive dykes, veins, or bosses, probably in close connection with former volcanic activity, as in the case of the dykes which in Arran traverse Lower Carboniferous rocks but are probably of Miocene age, and those which in Meissen send veins through and overspread the younger Palæozoic felsite-porphyries; (2) sheets which have flowed at the surface, as in the remarkable mass forming the Scuir of Eigg which has filled up a river-channel of Miocene age.[1]

Obsidian.—A volcanic glass representing the vitreous condition of a sanidine-rock, such as trachyte or liparite. It externally resembles

[1] *Quart. Journ. Geol. Soc.* 1871, p. 303.

bottle glass, having a perfect conchoidal fracture, and breaking into sharp splinters, semi-transparent or translucent at the edges. Its colours are black, brown, or greyish-green, rarely yellow, blue, or red, but not infrequently streaked or banded with paler and darker hues. A thin slice of obsidian prepared for the microscope is found to be very pale yellow, brown, grey, or nearly colourless, and on being magnified shows that the usual dark colours are almost always produced by the presence of minute opaque crystallites. Less frequently obsidian appears as a perfect glass without any foreign admixture. Its crystallites present themselves as black opaque trichites sometimes beautifully arranged in eddy-like lines showing the original fluid movement of the rock (Fig. 12); also as rod-like transparent microliths. They occasionally so increase in abundance as to make the rock lose the aspect of a glass and assume that of a dull flint-like or enamel-like stone. This devitrification can only be properly studied with the microscope. Again spherulites of a dull grey enamel appear in some parts of the rock so abundantly as to convert it into pearlstone. These spherulitic enclosures may be observed in Lipari in great abundance drawn out into layers so as to give the rock a fissile structure, while steam or gas cavities likewise occur sometimes so large and abundant as to impart a cellular aspect. Now and then the vapour vesicles are found in enormous numbers of extremely minute size, as in an obsidian from Iceland, a plane of which, about one square millimetre in size, has been estimated to include 800,000 pores. The average chemical composition of the rock is—silica, 71·0; alumina, 13·8; potash, 4·0; soda, 5·2; lime, 1·1; magnesia, 0·6; oxides of iron and manganese, 3·7; loss, 0·6; total, 100·0,—mean specific gravity, 2·40. Obsidian occurs as a product of the volcanoes of late geological periods. In Europe it is found in Lipari, Iceland, and Teneriffe; in North America it has been erupted from many points among the Western territories; it is met with also in New Zealand.[1]

Perlite (Pearlstone), another vitreous condition of sanidine lava, consists, as its name indicates, of enamel-like or vitreous globules, occasionally assuming polygonal forms by mutual pressure. These globules sometimes constitute the entire rock, their outer portions shading off into each other so as to form a compact mass; in other cases they are separated by and cemented in a compact glass or enamel. They consist of successive very thin shells, which, in a transverse section, are seen as concentric rings, usually full of the same kind of hair-like crystallites and crystals as in obsidian (Fig. 12). As these bodies both singly and in fluxion-streams traverse the globules, the latter may be conjectured to be a structure developed in the rock during its consolidation analogous to the concentric spheroidal structure seen in weathered basalt. Occasionally among these concentrically laminated globules are found true spherulites where the internal structure is radiating fibrous. A predominance of these bodies forms *spherulitic perlite* or *spherulite rock*.

[1] On obsidian, see Zirkel, *Micro. Petrog.*

Perlite is a markedly acid rock, its percentage of silica ranging between 70·6 and 82·8, and its average specific gravity between 2·37 and 2·46. It occurs most conspicuously in Hungary, where it takes

FIG. 22.—MICROSCOPIC STRUCTURE OF PERLITE.

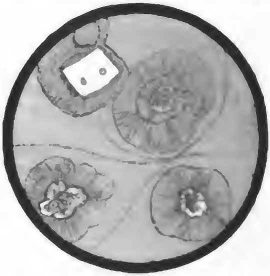

FIG. 23.—MICROSCOPIC STRUCTURE OF SPHERULITE-ROCK.

the form of lava streams proceeding from old trachyte volcanoes; also among the Euganean Hills, Ponza Islands and Ascension.[1]

Pumice (Ponce, Bimstein).—A general term for the loose, spongy, cellular, filamentous or froth-like parts of lavas. So distinctive is this structure, that the term *pumiceous* has come into general use to describe it. There can be no doubt that this froth-like rock owes its peculiarity to the abundant escape of steam or gas through its mass while still in a state of fusion. Microscopic examination reveals a glass crowded with enormous numbers of minute gas or vapour cavities usually drawn out in one direction, also abundant crystallites like those of obsidian. In the great majority of cases pumice is a form of the obsidians, possessing a percentage of silica from 58 to 74, and a specific gravity of 2·0 to 2·53, though, owing to its porous nature, it possesses great buoyancy and readily floats on water, drifting on the ocean to distances of many hundreds of miles from land, until the cells are gradually filled with water, when the floating masses sink to the bottom.[2] Abundant rounded blocks of pumice were dredged up by the *Challenger* from the floor of the Atlantic and Pacific Oceans. At Hawaii, some of the basic pyroxenic or olivine lavas give rise to a pumiceous froth.

b. Plagioclase Rocks.

The rocks of this division are of all ages up to the present time. They consist essentially of some triclinic felspar to which one, more usually several other silicates are added. As a rule

[1] Mr. Allport has described some ancient forms of perlite from Shropshire, *Q. J. Geol. Soc.* xxxiii. p. 449; and Mr. Rutley has shown the presence of perlitic structure among the Lower Silurian lavas of North Wales. *Op. cit.* xxxv p. 508.

[2] On porosity, hydration, and flotation of pumice, see Bischof, *Chem. und Phys. Geol.* Suppl. (1871) p. 177.

they are basic compounds, though in a few of them free quartz, as an original constituent, can be detected with or without the microscope. In structure they present a range similar to that of the orthoclase rocks. Some of them are thoroughly crystalline (diorite), though they never attain the coarseness of texture which is often reached by granite. Many of them are characteristically porphyritic (porphyrite), while in some cases they assume a completely vitreous texture (tachylite). They may be arranged in groups, according as the predominant mineral after the felspar is hornblende, mica, augite, or diallage.

Diorite (*Greenstone* in part).—A crystalline-granular aggregate of a triclinic felspar and hornblende, usually with magnetite and apatite. The proportions between the felspar and hornblende vary so greatly as to give rise to considerable differences in the colour and composition of the rock. The felspar when fresh shows its twin lamellations, but is frequently tinted green (from decomposition of the hornblende), and more or less decayed. The hornblende is dark green or black with vitreous lustre on the cleavage planes when fresh, but apt to decompose and to give rise to secondary products, such as epidote and chlorite. The apatite occurs in fine needles, usually only discernible under the microscope. There is commonly no trace of any base between the ingredients of the rock, which thus presents a thoroughly crystalline or granitoid structure. Average chemical composition:—silica, 54; alumina, 16·0—18; potash, 1·5—2·5; soda, 2—3; lime, 6—7·5; magnesia, 6·0; oxides of iron and manganese, 10—14; mean specific gravity about 2·95.

Among the varieties of diorite the following may be enumerated. *Quartz-diorite*, containing free quartz, usually only to be detected by microscopic examination. *Aphanite* (*aphanitic-diorite*) an exceedingly compact rock, in which the component minerals are not macroscopically distinguishable. A variety containing dispersed crystals of felspar or hornblende is termed *diorite-porphyry*. *Corsite*, a granitoid mixture of greyish-white anorthite, blackish-green hornblende and some quartz, which here and there have grouped themselves into globular aggregations (orbicular diorite, kugel-diorite, Napoleonite). *Mica-diorite*, containing abundant dark mica, which may even replace the hornblende.

Diorite occurs as an eruptive rock under conditions similar to those of quartz-porphyry and syenite. It is found among Palæozoic volcanic regions, as in North Wales, in "neck"-like masses which may mark the position of some of the volcanic orifices of eruption. It occurs also in association with granite and the crystalline schists in such a manner as to suggest a community of origin with these rocks.[1]

[1] On diorite, its structure and geological relations, consult the memoir on Belgian plutonic rocks by De la Vallée Poussin and A. Renard, *Mem. Acad. Royale Belg.* 1876; Behrens, *Neues Jahrb. Min.* 1871, p. 460; Zirkel, *Microscopical Petrog.* p. 83. J. A. Phillips, *Q. J. Geol. Soc.* xxxii. p. 155 and xxxiv. p. 471—valuable papers in which the constitution of some of the "greenstones" of the older geologists is clearly worked out. Many of these ancient rocks are there shown to be forms of doleritic lava, and the change of their original augite into hornblende is traced.

Hornblende andesite[1] consists of a triclinic felspar and hornblende, often with a little sanidine. The ground-mass is frequently quite crystalline, or shows a small proportion of a felsitic nature, with microliths and granules.

Two varieties are distinguished. (1) *Quartziferous* or *Dacite.*—This rock, besides the minerals enumerated, contains augite, magnetite, quartz and apatite in a ground-mass which has a felsitic, sometimes spherulitic, glassy, or finely granular base. Mean composition, silica, 66·10; alumina, 14·80; iron protoxide, 6·30; lime, 5·30; magnesia, 2·40; alkalies, 4·70; water, 0·50. Mean specific gravity, 2·60. (2) *Quartzless.*—This variety, sometimes distinctly crystalline, sometimes extremely compact, almost vitreous, contains crystals of plagioclase, hornblende, augite, and rarely sanidine, with not infrequently biotite, apatite, and tridymite, imbedded in a base composed of an aggregate of colourless felspar-microliths, and grains of magnetite. Mean composition, silica, 50·75; alumina, 17·25; oxides of iron, 7·57; lime, 6·0; magnesia, 1·30; potash, 3·10; alkalies, 4·0; water, 1·0. Specific gravity, 2·7—2·8.

Hornblende andesite is a volcanic rock of Tertiary and Post-tertiary date found in Hungary, Transylvania, Siebengebirge, and recently ascertained to have a considerable development in some of the western territories of the United States.

Propylite.—A name given to certain Tertiary volcanic rocks consisting of a triclinic felspar and hornblende in a fine-grained non-vitreous ground-mass. They are subject to considerable alteration, the hornblende being converted into epidote. Some quartziferous propylites have been described by Zirkel from Nevada, wherein the quartz abounds in liquid cavities containing briskly moving bubbles, and sometimes double enclosures with an interior of liquid carbon dioxide. The best account yet given of this rock will be found in Zirkel's *Microscopical Petrography*,[2] already cited. A specimen from Storm Cañon, Fish Creek Mountains, gave silica, 60·58; alumina, 17·52; ferric oxide, 2·77; ferrous oxide, 2·53; manganese, a trace; lime, 3·78; magnesia, 2·76; soda, 3·30; potash, 4·46; carbonic acid, a trace; loss by ignition, 2·25; specific gravity, 2·6—2·7.

Porphyrite.—This term may be used as the designation of rocks which consist essentially of some triclinic felspar, and show a true porphyry ground-mass containing crystals of plagioclase with magnetite or titaniferous iron, hornblende, augite, or mica. Thus defined, these rocks correspond in the plagioclase series to the orthoclase-porphyries and felsites of the orthoclase series. Their texture varies from coarse crystalline-granular to exceedingly close-grained, and passes occasionally even into vitreous. Porphyrite is a volcanic rock very characteristic of the later Palæozoic formations, occurring there

[1] See Zirkel, *Microscopical Petrog.* p. 122. King in vol. i. of *Explor. 40th Parallel*, p. 562.

[2] Vol. vi. of the *U. S. Exploration of the 40th Parallel*, p. 110. See also King in vol. i. p. 545, and C. E. Dutton's "High Plateaux of Utah" (*U. S. Geographical and Geological Survey of the Rocky Mountains*), chaps. iii. and iv.

as interstratified lava-beds, and in eruptive sheets, dykes, veins, and irregular bosses. In Scotland it forms masses, several thousand feet thick, erupted in the time of the Lower Old Red Sandstone, and others of wide extent, and several hundred feet in depth, belonging to the Lower Carboniferous period. In Germany it appears also at numerous points, where it is referred to later Palæozoic times.[1]

Porphyrite forms a connecting link between the hornblendic rocks and the augitic series next to be described.

Diabase.—This name has been given to certain dark green or black eruptive rocks found in the older geological formations, and consisting essentially of triclinic felspar, augite, magnetite or titaniferous iron, apatite, sometimes olivine, usually with more or less of diffused greenish substances (viridite) which have resulted from the alteration of the augite or olivine. The texture is sometimes quite crystalline; in other cases it shows a felsitic ground-mass. The average composition of typical diabase may be taken to be, silica, 48—50; alumina, 16·0; protoxide of iron, 12—15; lime, 5—11; magnesia, 4—6; potash, 0·8—1·5; soda, 3—4·5; water, 1·5—2. But there is generally carbonic acid present, united with some of the lime as a decomposition product.

Diabase is sometimes exceedingly fine-grained and compact (*diabase-aphanite*) assuming also a fissile character (*Diabas-schiefer*), or taking a porphyritic structure, and showing dispersed crystals of the component minerals (*diabase-porphyry, labrador-porphyry, augite-porphyry*); or its ingredients, as in some varieties of diorite, assume a concretionary arrangement (*variolite*). When the green compact ground-mass contains small kernels of carbonate of lime, sometimes in great numbers, it is called *calcareous aphanite* or *calc-aphanite*. Sometimes the rock is abundantly amygdaloidal. Though as a rule, free silica does not occur in it, some varieties have been found to contain this mineral, and are distinguished as *quartz-diabase*.

Diabase occurs both in contemporaneous beds and in intrusive dykes and sheets. It was formerly supposed to be confined to the older geological formations, while its place in Tertiary and recent times was taken by basalt. But some of the Miocene volcanic rocks of the west of Scotland are as good diabase as any among the Palæozoic formations; while, on the other hand, many of the dark heavy eruptive rocks belonging to the Carboniferous system in the basin of the Firth of Forth are unquestionable basalts. The main difference between diabase and basalt appears to be that the rocks included under the former name have undergone more internal alteration, in particular acquiring the diffused "viridite," so characteristic of them.[2]

Melaphyre.—This term has been so variously defined that the

[1] See an analysis of a porphyrite from the Vicentin, Von Lasaulx, *Z. Deutsch. Geol. Ges.* xxv. p. 323. On microscopic structure of porphyrite of Ilfeld, see A. Streng, *Neues Jahrb.* 1875, p. 785.

[2] The student will find in the *Zeitschrift Deutsch. Geol. Ges.*, 1874, p. 1, an important memoir by Dathe on the composition and structure of diabase. See also Zirkel's *Microscop. Petrog.* p. 97.

sense in which it is used requires to be explained. Senft[1] described melaphyre as an indistinctly mixed rock, dirty greenish-brown, or reddish-grey, or greenish black-brown to black; hard and tough when fresh (but also often with a pitchstone-like greasy lustre or like basalt), and showing crystals of reddish-grey labradorite, with magnetic titaniferous iron, and usually with carbonates of lime and iron, and ferruginous chlorite (delessite), and a crystalline granular or compact, earthy, porphyritic or amygdaloidal texture. Naumann defines melaphyre as a greenish, brownish or reddish-black micro-crystalline or crypto-crystalline, seldom slightly granular rock, with conspicuous dispersed crystals of labradorite, and less frequent and distinct crystals of pyroxene, not uncommonly rubellan or mica, but no quartz.[2] Zirkel in his first work called it a generally crypto-crystalline, sometimes porphyritic, very often amygdaloidal mixture consisting essentially of oligoclase and augite with magnetic iron.[3] In his more recent synopsis of the microscopic characters of rocks he admits the great diversity that has prevailed in the use of the term melaphyre, and the wide range of structure of the rocks that have been included under it. He regards the melaphyres as early precursors of the felspar-basalts, with but a rare development of a purely crystalline structure, and on the contrary a prominent non-individualized substance which may either be abundantly developed as a base or appear only sparingly between the crystals, and may be sometimes purely glassy, sometimes half-glassy, and sometimes completely devitrified.[4]

Rosenbusch, after a review of all the previous literature of the subject, proposes that the term melaphyre should be restricted to an older massive rock consisting essentially of plagioclase, augite, olivine, with free iron oxides and a porphyry base of any structure, and in variable proportions, and belonging for the most part to the age of the Carboniferous or older Permian, less frequently of the Triassic formations.[5] According to his arrangement, the old plagioclase-augite rocks are grouped in three sections; 1st, the granular section, including (*a*) Diabase, composed essentially of plagioclase and augite, and (*b*) olivine-diabase, composed of plagioclase, augite and olivine; 2nd the porphyritic section (with a ground-mass), comprising (*a*) diabase-porphyrite—a diabase having a porphyry ground-mass, (*b*) melaphyre, containing olivine in addition to the plagioclase and augite; 3rd, the vitreous section, in which the subordinate glassy varieties of the diabase-porphyrites are embraced.[6]

The attempt to base a classification of eruptive rocks upon chronological considerations has been fruitful of mistakes by leading to false assumption regarding the age of igneous rocks. The so-called melaphyres, like the diabases, do not differ in any essential feature of structure or composition from the basalts. So entirely is this

[1] *Classification der Felsarten*, 1857, p. 263.
[2] *Geol.* i. p. 587.
[3] *Petrographie*, ii. p. 39.
[4] *Mik. Beschaff.* p. 411.
[5] *Mik. Physiog.*, p. 392.
[6] *Op. cit.* p. 317.

the case, that, as above remarked, rocks now known to be of Tertiary date, have been described as melaphyres, while others of Lower Carboniferous age have been unhesitatingly referred to as basalts.[1]

Augite-Andesite is the name given to certain dark eruptive rocks of Tertiary and post-Tertiary date, which consist of a triclinic felspar (oligoclase, or some species rather richer in silica than labradorite) and augite, with sometimes sanidine, hornblende, biotite, magnetite, or apatite, and in some varieties quartz. The ground-mass is resolvable under the microscope, sometimes into a glassy sometimes into a more or less fully devitrified base. The quartz-bearing varieties contain from 63 to 67 per cent. of silica, and in this respect, as well as in the failure of olivine, are distinguished from the basalts. The average composition of the quartzless varieties may be thus given: Silica, 57·15; alumina, 16·10; protoxide of iron, 13·0; lime, 5·75; magnesia, 2·21; potash, 1·81; soda, 3·88; mean specific gravity, 2·75—2·85.

Augite-Andesite occurs in dykes, lava streams, plateaux, sheets and neck-like bosses in regions of extinct and active volcanoes, as in Transylvania and Hungary, Santorin, Iceland, Teneriffe, the Western Territories of North America, the Andes, New Zealand, &c.

Basalt-Rocks.[2]—Under this title is embraced an important and widespread series of volcanic rocks, which consist essentially of some

FIG. 24.—MICROSCOPIC STRUCTURE OF BASALT.

The large shaded Crystals are Olivine considerably serpentinized; the numerous small white Prisms are Plagioclase. A few Augite prisms occur which, to the right of the centre of the drawing, are aggregated into a large compound crystal. The black specks are Magnetite.

triclinic felspar, augite, olivine, magnetite or titaniferous iron, frequently with apatite, sometimes with sanidine or nepheline.

[1] *Ante* pp. 109, 145. See also *Trans. Roy. Soc. Edin.*, vol. xxix. p. 499.

[2] On basalt rocks see Zirkel's *Basaltgesteine*, 1870. *Boricky's* "Petrographische Studien an den Basaltgesteinen Böhmens," in *Archiv. für Naturwiss. Landesdurchforschung von Böhmen*, ii. 1873. Allport, *Q. J. Geol. Soc.* xxx. p. 529. Geikie, *Trans. Roy. Soc. Edin.* xxix. Möhl, *Nov. Act. Acad. Leop. Carol.* xxxvi. (1873) p. 74; *Neues Jahrb.* 1873, pp. 449, 824

Four varieties are distinguished according to texture: dolerite, anamesite, basalt, and vitreous basalt.

Dolerite (*greenstone*, in part, of older authors). This includes all the larger-grained kinds in which the component crystals can be readily distinguished with the naked eye. The felspar, which among the basalt-rocks is probably often a more silicated form than labradorite, is usually the most conspicuous ingredient, the dark prisms of augite, and the dusty or minutely octahedral magnetite give the grey or black hue to the rock. The microscopic structure is crystalline, though a small quantity of an amorphous base may here and there be traced (Fig. 11).

Anamesite includes those kinds of which the texture is so fine that the naked eye can observe only that the mass is a finely crystallised granular aggregate. Under the microscope more of an amorphous base with microliths is seen than in dolerite.

Basalt.—This name when used as the designation of a particular rock is applied to those black, extremely compact, apparently homogeneous varieties which break with a splintery or conchoidal fracture. The component minerals can only be observed with the microscope, unless where they are scattered porphyritically through the mass. They consist of those above mentioned, and between them may be traced a base which is sometimes a glass, but is often partially devitrified by the appearance of various crystallites. These sometimes so increase that the glass disappears, and its place is taken by an aggregate of minute granules, hairs,

Fig. 25.—Junction of intrusive Dolerite with Sandstone, Salisbury Crag, Edinburgh. Magnified 20 Diameters.

The granular portion at the bottom of the drawing is Sandstone, a part of which is involved in the Dolerite that occupies the rest of the slide. The darker portion next the Sandstone is a vitreous substance which has been serpentinized. It contains crystals of Plagioclase and vapour vesicles drawn out in the direction of flow. Above the darker part the glassy condition rapidly passes into ordinary but minutely crystalline Dolerite. The rock has been considerably altered, calcite occupying many of the vesicles and fissures.

needles and crystals. The proportion of this base varies within wide limits, insomuch that while in some basalts it so preponderates

that the individual crystals are scattered widely through it or drawn out into beautiful streaks and eddies of fluxion structure, in others it almost or wholly disappears, and the rock then appears as a nearly or quite crystalline mass.

Vitreous Basalt. (*Tachylite, Hyalomelan.*) In some cases basalt passes into a condition which, even to the naked eye, is recognizable as that of a true glass. This more especially takes place along the edges of dykes and intrusive sheets. Where an external skin of the original molten rock has rapidly cooled and consolidated in contact with the rocks through which the eruption took place, a transition can be traced within the space of less than a quarter of an inch from a crystalline dolerite, anamesite or basalt, into a black glass, which, under the microscope, assumes a pale brown or yellowish colour, and is isotropic, but generally contains abundant microliths, sometimes with a globular or spherulitic concretionary structure. In such cases it seems indisputable that this glass represents what was the general condition of the whole molten mass at the time of eruption, and that the present crystalline structure of the rock was developed during cooling and consolidation. It is worthy of remark that in the analyses of vitreous basalts the percentage of silica rises usually above that of ordinary crystalline basalt. The average composition of the basalt rocks is shown in the subjoined Table:

	Silica.	Alumina.	Lime.	Magnesia.	Oxides of Iron and Manganese.	Potash.	Soda.	Loss by ignition (water, &c.).	Specific gravity.
Dolerite . .	45—55	12—16	7—13	3—9	9—18	0—1	2—5	0·5—3	2·75—2·96
Anamesite . .	46—53	12—15	8·5—13	1·5—9·5	10—15	0·5—1	2—3	1—3	2·7—2·8
Basalt . . .	45—55	10—18	7—14	3—10	9—16	0·5—3	2—5	1—5	2·85—3·10
Vitreous Basalt	48—58	12—17	6·5—9·5	0·5—6	8—20	0·5—9·5	2·5—5	0·5—3·5	2·6—2·7

The basalt-rocks are thoroughly volcanic rocks, appearing in lava-streams, sheets, plateaux, dykes, and veins. The finer grained varieties are often beautifully columnar; hence the term "basaltic" has been popularly used to denote the columnar structure. Porphyritic and amygdaloidal varieties are of frequent occurrence.

As already stated, it has been assumed by some writers that basalt did not begin to be erupted until the Tertiary period. But true basalt occurs abundantly in Scotland, as a product of Lower Carboniferous volcanoes. There seems, however, to be no doubt that, as Richthofen first pointed out, in the order of appearance at any given volcanic focus, basalt comes up after the rhyolitic and trachytic eruptions have ceased. (See Book III. Part I. Section i. § 5.)

Zirkel has divided basalt into felspar-basalt, which is the rock now described; nepheline-basalt and leucite-basalt. The two latter rocks, in which the part of the felspar is played by nepheline and leucite respectively, are enumerated on the next page.

Gabbro (Diallage Rock) is a thoroughly crystalline granitoid

aggregate of a triclinic felspar (sometimes, however, saussurite) and diallage or smaragdite. The felspar (usually taken to be labradorite) occurs in distinct crystals or crystalline aggregates of grey, white or violet tint, and under the microscope is sometimes found to be crowded with crystallites. The saussurite is likewise light-coloured, while the diallage is distinguishable by its dirty-green or brown tint, the metalloidal or pearly lustre on its cleavage planes, and the frequent presence of layers of microscopic dark brown or black lamellæ. Some varieties contain abundant olivine. Average composition—silica, 49; alumina, 15; lime, 9·5; magnesia, 9·7; oxides of iron and manganese, 11·5; potash, 0·3; soda, 2·5; loss by ignition, 2·5; specific gravity, 2·85—3·10.

Gabbro occurs (1) in association with granite, gneiss, and other crystalline rocks as large irregular bosses (Saxony, Silesia, the Harz, &c.), and (2) in large sheets and bosses associated with volcanic eruptive rocks. In the latter case it occurs in Skye and Mull connected with Miocene volcanic outflows.[1]

Hypersthenite, allied to gabbro, is a granular granitoid aggregate of labradorite and hypersthene, found in beds, bosses, and veins, in Norway, Greenland, and Labrador.

(2) Nepheline Rocks.

Under this name is grouped a series of distinctly crystalline and also compact dark rocks composed of nepheline, augite, and magnetite, often with olivine, sometimes with a little triclinic felspar. They are thus distinguished by the fact that in them the part taken by felspar in the rocks already enumerated is supplied by nepheline. They are usually divided into nepheline-dolerite, a crystalline granular aggregate closely resembling in general character true dolerite; and nepheline-basalt, a black, heavy compact rock not to be outwardly distinguished from ordinary felspar-basalt. They are volcanic masses of late Tertiary age, but occur much more sparingly than the true basalts. They are found in the Thuringer Wald, Erzgebirge, Baden, &c.

(3) Leucite Rocks.

This division includes certain grey or black crystalline or compact volcanic rocks resembling some of the basalt series, but distinguished from them by the predominance of leucite. The more crystalline-granular varieties, named leucitophyre or leucite-porphyry, are composed of a characteristically dull grey aggregate of leucite, augite, and magnetite, with sometimes a little nepheline, olivine, or mica. The leucite occurs in well-defined garnet-like crystals of a dull white colour, sometimes an inch in diameter, not infrequently broken and with fissures interpenetrated by the surrounding ground-mass. The rock is

[1] On gabbro, see Lang, *Z. Deutsch. Geol. Ges.* xxxi. p. 484.

one of the products of the active and extinct volcanoes of Southern Italy. Leucite-basalt is to outward appearance quite like true basalt, and occurs under similar conditions, but is less widely distributed than even nepheline-basalt. Under the microscope it presents a finely crystalline structure with little trace of any amorphous base, and abundant minute sections of the characteristic leucite. This rock occurs among the extinct volcanic cones of the Eifel, in the Thuringer Wald, and in the Italian volcanic districts (Albano, Capo di Bove). Leucite-rocks, so far as known, occur only among later Tertiary and recent volcanic products.

(4.) Olivine Rocks.

This division embraces a series of crystalline rocks composed essentially of olivine, with usually one or two other magnesian silicates. Rocks of this type have been classed by Rosenbusch under the general name of *Peridotites*. The following are the more important species:—

Pikrite, a rock rich in olivine, usually more or less serpentinized, with augite, magnetite, or ilmenite, and a little brown biotite, hornblende, or apatite; eulysite, a mixture of olivine, augite, and red garnet; garnet-olivine-rock, composed of olivine, diallage, and garnet; olivine-enstatite-rock consisting of olivine and enstatite (bronzite or hypersthene) with magnetite or chromite; lherzolite, a mixture of olivine, pyroxene, picotite, and usually some magnetite[1]; dunite, a mixture of olivine and chromite, found with serpentine; limburgite, composed of crystals of olivine, augite, and magnetite, in a base more or less vitreous.

One of the most remarkable features about these rocks is their frequent association with serpentine and their tendency to pass into that rock. There can indeed be no doubt that, as Tschermak first pointed out, many serpentines were once olivine rocks.

(5.) Serpentine Rocks.

Under this name may be included rocks which, whatever may have been their original character and composition, now consist mainly or wholly of serpentine. As already stated, olivine readily passes into the condition of serpentine, and many serpentine rocks originally consisted principally of olivine. This mineral may be changed into serpentine, while the other minerals remain nearly unaffected, as is admirably seen in pikrite. If varieties due to different phases of alteration were judged worthy of separate designation, each member of the olivine rocks might of course have a conceivable or actual representative among the serpentine series. But, without attempting this minuteness of classification, we may with advantage treat by itself, as deserving special notice, the massive

[1] Bonney, *Geol. Mag.* iv. 2nd ser. p. 59.

form of the mineral serpentine to whatsoever cause its mode of formation may be assigned.

Serpentine,[1] a compact or finely granular, faintly glimmering, or dull rock, easily cut or scratched, having a prevailing dirty-green colour, sometimes variously streaked or flecked with brown, yellow, or red. It is a massive form of the mineral serpentine, but frequently contains other minerals. One of its commonest accompaniments is chrysotile or fibrous serpentine, which in veinings of a silky lustre often ramifies through the rock in all directions. Other common enclosures are olivine, bronzite, enstatite, magnetite, and chromic iron.

Serpentine occurs in two distinct forms; first, in beds or indefinitely-shaped bosses, intercalated among schistose rocks, and associated especially with crystalline limestones; second, in dykes or veins traversing other rocks.

As to its mode of origin, there can be no doubt that in some cases it was originally an eruptive rock. In the Old Red Sandstone of Forfarshire and Kincardineshire it is found in dykes traversing the sandstones and conglomerates. The frequent occurrence of recognizable olivine crystals or of their still remaining contours in the midst

Fig. 26.—Microscopic Structure of Serpentine (20 Diameters).

of the serpentine matrix affords likewise good grounds for assigning an eruptive origin to many serpentines which have no distinctly eruptive external form. The rock cannot of course have been ejected as the hydrous magnesian silicate serpentine, but it may have been originally essentially an olivine rock, and as such may have been injected in the form of sheets or dykes into the overlying crust. But, on the other hand, the intercalation of beds of serpentine among schistose rocks, and particularly the frequent occurrence of serpentine in connection with more or less altered limestones (West of Ireland, Highlands of Scotland, Ayrshire), suggests another mode of origin in these cases. Some writers have contended that such serpentines

[1] See Tschermak, *Sitz. Akad. Wien*, lvi. July, 1867; Bonney, *Q. J. Geol. Soc.* xxxiii. p. 884, xxxiv. p. 769; *Geol. Mag.* vi. p. 362; Michel-Lévy, *Bull. Soc. Géol. France*, vi. 3rd ser. p. 156.

are products of the alteration of dolomite, the magnesia having been taken up by silica, leaving the carbonate of lime behind as beds of limestone. It is conceivable, however, that in some cases at least the serpentines were an original deposit from oceanic water, as has been suggested by Sterry Hunt in the case of those associated with the crystalline schists.[1] The beds of serpentine intercalated with limestone may have been due to the elimination of magnesian silicates from sea-water by organic agency, like the glauconite now found filling the chambers of *foraminifera*, the cavities of corals, the canals in shells and sea-urchin spines and other organisms on the floor of the present sea.[2] Among the limestones and crystalline schists of Banffshire serpentine occurs in thick lenticular beds which possess a schistose crumpled structure and agree in dip with the surrounding rocks. They may have been deposits of contemporaneous origin with the limestones and schists among which they occur, and in association with which they have undergone the characteristic schistose puckering and crumpling.

B. FRAGMENTAL (CLASTIC).

This great series embraces all rocks of a secondary or derivative origin; in other words, all formed of particles which have previously existed on or beneath the surface of the earth in another form, and the accumulation and consolidation of which gives rise to new compounds. Some of these materials have been produced by the mechanical action of wind, as in the sand-hills of sea-coasts and inland deserts (Æolian rocks); others by the operation of moving water, as the gravel, sand and mud of shores and river beds (aqueous sedimentary rocks); others by the accumulation of the entire or fragmentary remains of once living plants and animals (organic rocks); while yet another series has arisen from the gathering together of the loose débris thrown out by volcanoes (volcanic tuffs). It is evident that in dealing with these various detrital formations the degree of consolidation is of secondary importance. The soft sand and mud of a modern lake-bottom differ in no essential respect from ancient lacustrine strata, and may tell their geological story equally well. No line is to be drawn between what is popularly termed rock and the loose as yet uncompacted débris out of which solid rocks may eventually be formed. Hence in the following arrangement the modern and the ancient, being one in structure and mode of formation, are classed together.

It will be observed that in several directions we are led by the fragmental rocks back to those stratified deposits with which we began at p. 110. Both series of deposits are accumulated simultaneously and are often interstratified; and, as we have seen, the

[1] *Chemical Essays*, p. 123.
[2] According to Berthier, one of the glauconitic deposits in a tertiary limestone is a true serpentine. See Sterry Hunt, *Chem. Essays*, p. 303.

calcareous organic fragmental rocks (p. 107) actually undergo a gradual internal change which more or less effaces their detrital origin, and gives them such a crystalline character as to entitle them to be ranked among the crystalline limestones (p. 112).

1. Gravel and Sand Rocks (Psammites).

As the deposits included in this subdivision are produced by the disintegration and removal of rocks by the action of the atmosphere, rain, rivers, frost, the sea, and other superficial agencies, they are mere mechanical accumulations, and necessarily vary indefinitely in composition, according to the nature of the sources from which they are derived. As a rule they consist of the detritus of siliceous rocks, these being among the most durable materials. Quartz, in particular, enters largely into the composition of sandy and gravelly detritus. Fragmentary materials tend to group themselves according to their size and relative density. Hence they are apt to occur in layers, and to show the characteristic *stratified* arrangement of *sedimentary* rocks. They may enclose the remains of any plants or animals entombed on the same sea-floor, river-bed, or lake-bottom.

Cliff-débris. Moraine-stuff.—Angular rubbish disengaged by frost and ordinary atmospheric waste from cliffs, crags, and steep slopes. It slides down the declivities of hilly regions, and accumulates at their base, until washed away by rain or by brooks. It forms talus slopes of as much as 40°, though for short distances, if the blocks are large, the general angle of slope may be much steeper. It naturally depends for its composition upon the nature of the solid rocks from which it is derived. The material constituting glacier moraines is of this kind; it may be deposited near its source or may be transported for many miles on the surface of the ice.

Perched Blocks, Erratic Blocks.—Large masses of rock, often as big as a house, which have been transported by glacier-ice, and have been lodged in a prominent position in glacier valleys or have been scattered over hills and plains. An examination of their mineralogical character leads to the identification of their source and, consequently, to the path taken by the transporting ice. (See Book III. Part II. Section ii. § 5.)

Rain-wash.—A loam or earth which accumulates on the lower parts of slopes or at their base, and is due to the gradual descent of the finest particles of disintegrated rocks by the transporting action of rain. Brick-earth is the name given in the south-east of England to thick masses of such loam which are extensively used for making bricks.

Soil.—The product of the subaerial decomposition of rocks and of the decay of plants and animals. Primarily the character of the soil is determined by that of the subsoil, of which indeed it is merely a further disintegration. The formation of soil is treated in Book III. Part II. Section ii. § i.

Subsoil.—The broken-up part of the rocks immediately under the soil. (See Fig. 92.) Its character of course is determined by that of the rock out of which it is formed by subaerial disintegration.

Blown Sand.—Loose sand usually arranged in lines of dunes, fronting a sandy beach or in the arid interior of a continent. It is piled up by the driving action of wind (Book III. Part II. Section i.). It varies in composition, being sometimes entirely siliceous, as upon shores where siliceous rocks are exposed; sometimes calcareous, where derived from triturated shells, nullipores, or other calcareous organisms. Layers of finer and coarser particles often alternate, as in water-formed sandstone. On many coast-lines in Europe grasses and other plants bind the surface of the shifting sand. These layers of vegetation are apt to be covered by fresh encroachments of the loose material, and then by their decay to give rise to dark peaty seams in the sand. Calcareous blown sand is compacted into hard stone by the action of rain-water, which alternately dissolves a little of the lime and re-deposits it on evaporation as a thin crust cementing the grains of sand together. In the Bahamas and Bermudas, extensive masses of calcareous blown sand have been cemented in this way into solid stone, which weathers into picturesque crags and caves like a limestone of older geological date.[1]

Gravel, shingle.—Names applied to the coarser kinds of rounded waterworn detritus. In gravel the average size of the component pebbles ranges from that of a small pea up to about that of a walnut, though of course many included fragments will be observed which exceed these limits. In shingle the stones are coarser, ranging up to blocks as big as a man's head or larger. These names are applied quite irrespective of the composition of the fragments, which varies greatly from point to point. As a rule the stones consist of hard crystalline rocks, since these are best fitted to withstand the powerful grinding action to which they are exposed.

River-sand, Sea-sand.—When the rounded water-worn detritus is finer than that to which the term gravel would be applied it is called sand, though there is obviously no line to be drawn between the two kinds of deposit, which necessarily graduate into each other. The particles of sand range down to such minute forms as can only be distinctly discerned with a microscope. The smaller forms are generally less well rounded than those of greater dimensions, no doubt because their diminutive size allows them to remain suspended in agitated water, and thus to escape the mutual attrition to which the larger and heavier grains are exposed upon the bottom (Book III. Part II. Section ii.). So far as experience has yet gone, there is no method by which inorganic sea-sand can be distinguished from that of rivers or lakes. As a rule, sand consists largely (often wholly) of quartz-grains. The presence of fragments of marine shells will of course betray its salt-water origin; but in the trituration to which

[1] For interesting accounts of the Æolian deposits of the Bahamas and Bermudas, see Nelson, *Q. J. Geol. Soc.* ix. p. 200, and Sir Wyville Thomson's "Atlantic," vol. i.

sand is exposed on a coast-line the shell-fragments are in great measure ground into calcareous mud and removed.

Mr. Sorby has recently shown that by microscopic investigation much information may be obtained regarding the history and source of sedimentary materials. He has studied the minute structure of modern sand, and finds that sand-grains present the following five distinct types, which, however, graduate into each other.

1. Normal, angular, fresh-formed sand, such as has been derived almost directly from the breaking up of granitic or schistose rocks.

2. Well-worn sand in rounded grains, the original angles being completely lost, and the surfaces looking like fine ground glass.

3. Sand mechanically broken into sharp angular chips, showing a glassy fracture.

4. Sand having the grains chemically corroded, so as to produce a peculiar texture of the surface, differing from that of worn grains or crystals.

5. Sand in which the grains have a perfectly crystalline outline, in some cases undoubtedly due to the deposition of quartz upon rounded or angular nuclei of ordinary non-crystalline sand.[1]

The same acute observer points out that, as in the familiar case of conglomerate pebbles, which have sometimes been used over again in conglomerates of very different ages, so with the much more minute grains of sand, we must distinguish between the age of the grains and the age of the deposit formed of them. An ancient sandstone may consist of grains that had hardly been worn before they were finally brought to rest, while the sand of a modern beach may have been ground down by the waves of many successive geological periods.

Sand taken by Mr. Sorby from the old gravel terraces of the River Tay was found to be almost wholly angular, indicating how little wear and tear there may be among particles of quartz $\frac{1}{100}$ of an inch in diameter, even though exposed to the drifting action of a rapid river.[2] Sand from the boulder clay at Scarborough was likewise ascertained to be almost entirely fresh and angular. On the other hand, in geological formations, which can be traced in a given direction for several hundred miles, a progressively large proportion of rounded particles may be detected in the sandy beds, as Mr. Sorby has found in following the greensand from Devonshire to Kent.

The following names are applied to forms of sandy or gravelly detritus when consolidated.

Conglomerate (Puddingstone)—A name given to any rock formed of consolidated gravel or shingle. The component pebbles are rounded and waterworn. They may consist of any kind of rock, though usually of some hard and durable sort, such as quartz or quartz-rock. A special name may be given according to the nature of the pebbles, as quartz-conglomerate, limestone-conglomerate,

[1] Address, *Q. J. Geol. Soc.* xxxvi. 1880, p. 58. [2] See Book III. Part II., Sections ii. § iii

granite-conglomerate, &c. or according to that of the paste or cementing matrix which may consist of a hardened sand or clay, and may be siliceous, calcareous, argillaceous, or ferruginous. In the coarser conglomerates, where the blocks may exceed six feet in length, there is often very little indication of stratification. Except where the flatter stones show by their general parallelism the rude lines of deposit, it may be only when the mass of conglomerate is taken as a whole, in its relation to the rocks below and above it, that its claim to be considered a bedded rock will be conceded. The occurrence of occasional bands of conglomerate in a series of arenaceous strata is analogous probably to that of a shingle bank or gravel beach on a modern coast-line. But it is not easy to understand the circumstances under which some ancient conglomerates accumulated, such as that of the Old Red Sandstone of central Scotland, which attains a thickness of many thousand feet, and consists of well rounded and smoothed blocks often several feet in diameter.

In many old conglomerates (and even in those of Miocene age in Switzerland) the component pebbles may be observed to have indented each other. In such cases also they may be found split and recemented; sometimes the same pebble has been crushed into a number of pieces, which are held together by a retaining cement. These phenomena point to great pressure, and some internal relative movement in the rocks. (Book III. Part I. Section iv. § 3.)

Breccia.—A rock composed of angular instead of rounded fragments. It commonly presents less trace of stratification than conglomerate. Intermediate stages between these two rocks, where the stones are partly angular and partly subangular and rounded, are known as *brecciated conglomerate.* Considered as a detrital deposit formed by superficial waste, breccia points to the disintegration of rocks by the atmosphere, and the accumulation of their fragments with little or no intervention of running water. Thus it may be formed at the base of a cliff either subaerially, or where the débris of the cliff falls at once into a lake or into deep sea-water.

The term Breccia has, however, been applied to rocks formed in a totally different manner. Intrusive igneous masses have sometimes torn off fragments of the rocks through which they have ascended, and these angular fragments have been enclosed in the liquid or pasty mass. Or the intrusive rock has cooled and solidified externally while still mobile within, and in its ascent has caught up and involved some of these consolidated parts of its own substance. Again, where solid masses of rock within the crust of the earth have ground against each other, as in dislocations, angular fragmentary rubbish has been produced, which has subsequently been consolidated by some infiltrating cement (fault-rock). It is evident, however, that breccia formed in one or other of these hypogene ways will not as a rule be apt to be mistaken for the true breccias, arising from superficial disintegration.

Sandstone (Grès).—A rock composed of consolidated sand. As in ordinary modern sand, the integral grains of sandstone are chiefly quartz, which must here be regarded as the residue left after all the more decomposable minerals of the original rocks have been carried away in solution or in suspension as fine mud. The colours of sandstones arise, not so much from that of the quartz, which is commonly white or grey, as from the film or crust which often coats the grains and holds them together as a cement. Iron, the great colouring ingredient of rocks, gives rise to red, brown, yellow, and green hues, according to its degree of oxidation and hydration.

Like conglomerates, sandstones differ in the nature of their component grains, and in that of the cementing matrix. Though consisting for the most part of siliceous grains, they include others of clay, felspar, mica, or other mineral; and these may increase in number so as to give a special character to the rock. Thus sandstones may be argillaceous, felspathic, micaceous, calcareous, &c. By an increase in the argillaceous constituents, a sandstone may pass into one of the clay-rocks, just as modern sand on the sea-floor shades imperceptibly into mud. On the other hand, by an augmentation in the size of the grains, a sandstone may become a *grit*, or a pebbly or conglomeratic sandstone, and pass into a fine conglomerate. A piece of fine-grained sandstone seen under the microscope looks like a coarse conglomerate, so that the difference between the two rocks is little more than one of relative size of particles.

The cementing material of sandstones may be *ferruginous*, as in most ordinary red and yellow sandstones, where the anhydrous or hydrous iron oxide is mixed with clay or other impurity—in red sandstones the grains are held together by a hæmatitic, in yellow sandstones by a limonitic cement; *argillaceous*, where the grains are united by a base of clay, recognizable by the earthy smell when breathed upon; *calcareous*, where carbonate of lime occurs either as an amorphous paste or as a crystalline cement between the grains; *siliceous*, where the component particles are bound together by a flinty substance, as in the exposed blocks of eocene sandstone known as "grey-weathers" in Wiltshire, and which occur also over the North of France towards the Ardennes.

Among the varieties of sandstone the following may here be mentioned. Flagstone—a thin bedded sandstone, capable of being split along the lines of stratification into thin beds or flags; Micaceous sandstone (*mica-psammite*)—a rock so full of mica-flakes that it splits readily into thin laminæ, each of which has a lustrous surface from the quantity of silvery mica. This rock is called "fakes" in Scotland. Freestone—a sandstone (the term being applied sometimes also to limestone) which can be cut into blocks in any direction, without a marked tendency to split in any one plane more than in another. Though this rock occurs in beds, each bed is not divided into laminæ, and it is the absence of this minor stratification which makes the stone so useful for architectural

purposes (Craigleith and other sandstones at Edinburgh, some of which contain 98 per cent. of silica). Glauconitic sandstone (green-sand)—a sandstone containing kernels and dusty grains of glauconite, which imparts a general greenish hue to the rock. The glauconite has probably been deposited through organic agency, as in the case of the green matter filling echinus-spines, foraminifera, shells and corals on the floor of the present ocean.[1] Buhrstone—a highly siliceous, exceedingly compact though cellular rock (with *Chara* seeds, &c.), found alternating with unaltered Tertiary strata in the Paris basin, and forming from its hardness and roughness an excellent material for the grindstones of flour-mills may be mentioned here; it probably has been formed by the precipitation of silica by the action of organisms. Arkose (*granitic sandstone*)—a rock composed of disintegrated granite, and found in geological formations of different ages, which have been derived from granitic rocks. Crystallized sandstone—an arenaceous rock in which a deposit of crystalline quartz has taken place upon the individual grains, each of which becomes the nucleus of a more or less perfect quartz crystal. Mr. Sorby has observed such crystallized sand in deposits of various ages, from the Oolites down to the Old Red Sandstone.[2]

Greywacke.—A compact aggregate of rounded or subangular grains of quartz, felspar, slate, or other minerals or rocks cemented by a paste which is usually siliceous but may be argillaceous, felspathic, calcareous, or anthracitic (Fig. 13). Grey, as its name denotes, is the prevailing colour; but it passes into brown, brownish-purple, and sometimes, where anthracite predominates, into black. The rock is distinguished from ordinary sandstone by its darker hue, its hardness, the variety of its component grains, and above all by the compact cement in which the grains are imbedded. In many varieties so pervaded is the rock by the siliceous paste that it possesses great toughness, and its grains seem to graduate into each other as well as into the surrounding matrix. Such rocks when fine-grained can hardly, at first sight or with the unaided eye, be distinguished from some compact igneous rocks, though a microscopic examination at once reveals their fragmental character. In other cases, where the greywacke has been formed mainly out of the débris of granite, quartz-porphyry, or other felspathic masses, the grains consist so largely of felspar, and the paste also is so felspathic, that the rock might be mistaken for some close-grained granular porphyry. Greywacke occurs extensively among the Palæozoic formations in beds alternating with shales and conglomerates. It represents the muddy sand of some of the Palæozoic sea-floors, retaining often its ripple-marks and sun-cracks. The metamorphism it has undergone has generally not been great, and for the most part is limited to induration, partly by pressure and partly by permeation of a siliceous cement. But where felspathic ingredients prevail, the rock has offered facilities for alteration, and has

[1] See Sollas, *Geol. Mag.* iii. new ser. p. 539.
[2] *Q. J. Geol. Soc.* xxxvi. p. 63. See Daubrée, *Ann. des Mines*, 2nd ser. i. p. 206.

been here and there changed into gneiss and even into rocks which graduate into granite.

The more fissile fine-grained varieties of this rock have been termed greywacke-slate. In these, as well as in greywacke, organic remains occur among the Silurian and Devonian formations. Sometimes in the Lower Silurian rocks of Scotland these strata become black with carbonaceous matter, among which vast numbers of graptolites may be observed.

2. **Clay Rocks** (Pelites).

These are composed of the finer argillaceous sediments or mud derived from the waste of rocks. Perfectly pure clay or kaolin, hydrated silicate of alumina (silica 47·05, alumina 39·21, water 13·74), may be seen where granites and other felspar-bearing rocks decompose. But, as a rule, the argillaceous materials are mixed with various impurities.

Clay, Mud.—The decomposition of felspars and allied minerals gives rise to the formation of hydrous aluminous silicates, which occurring usually in a state of very fine subdivision, are capable of being held in suspension in water, and of being transported to great distances. These substances differing much in composition, are embraced under the general term Clay, which may be defined as a white, grey, brown, red, or bluish substance, which when dry is soft and friable, adheres to the tongue, and shaken in water makes it mechanically turbid; when moist is plastic, when mixed with much water becomes mud. It is evident that a wide range is possible for varieties of this substance. The following are the more important.

Pipe-clay.—White, nearly pure, and free from iron.

Fire-clay.—A deposit largely found in connexion with coal-seams, contains little iron, and is nearly free from lime and alkalies. Some of the most typical fire-clays are those long used at Stourbridge, Worcestershire, for the manufacture of pottery. The best glass-house pot-clay, that is, the most refractory, and therefore used for the construction of pots which have to stand the intense heat of a glass-house, has the following composition:—silica, 73·82; alumina, 15·88; protoxide of iron, 2·95; lime, trace; magnesia, trace; alkalies, ·90; sulphuric acid, trace; chlorine, trace; water, 6·45; specific gravity, 2·51.

Gannister.—A very siliceous close-grained variety, found in the Lower Coal-measures of the north of England, and now largely ground down as a material for the hearths of iron furnaces.

Brick-clay.—Properly rather an industrial than a geological term, since it is applied to any clay, loam, or earth, from which bricks or coarse pottery are made. It is an impure clay, containing a good deal of iron, with other ingredients. An analysis gave the following composition of a brick-clay: silica, 49·44; alumina, 34·26; sesquioxide of iron, 7·74; lime, 1·48; magnesia, 5·14; water, 1·94.

Fuller's Earth (Terre à foulon, Walkerde).—A greenish or brownish earthy, soft, somewhat unctuous substance, with a shining streak, which does not become plastic with water, but crumbles down into mud. It is a hydrous aluminous silicate with some magnesia, iron-oxide and soda. The yellow fuller's earth of Reigate contains silica 44, alumina 11, oxide of iron 10, magnesia 2, lime 5, soda 5.[1] In England fuller's earth occurs in beds among the Jurassic and Cretaceous formations. In Saxony it is found as a result of the decomposition of diabase and gabbro.

Wacke.—A dirty green to brownish-black earthy or compact, but tender and apparently homogeneous clay, which arises as the ultimate stage of the decomposition of basalt-rocks *in situ*.

Till, Boulder-clay.—A stiff sandy and stony clay, varying in colour and composition, according to the character of the rocks of the district in which it lies. It is full of worn stones of all sizes, up to blocks weighing several tons, and often well smoothed and striated. It is a glacial deposit, and will be described among the formations of the Glacial Period.

Mudstone.—A fine, usually more or less sandy, argillaceous rock, having no fissile character, and of somewhat greater hardness than any form of clay. The term Clay-rock has been applied by some writers to an indurated clay requiring to be ground and mixed with water before it acquires plasticity.

Shale (Schiste, Schieferthon).—A general term to describe clay that has assumed a thinly stratified or fissile structure. Under this term are included laminated and somewhat hardened argillaceous rocks which are capable of being split along the lines of deposit into thin leaves. They present almost endless varieties of texture and composition, passing on the one hand into clays, or, where much indurated, into slates and argillaceous schists, on the other into flagstones and sandstones, or again, through calcareous gradations into limestone, or through ferruginous varieties into clay-ironstone, and through bituminous kinds into coal. Some of the altered kinds of clay-rocks have already been described. Flinty-slate or Lydian-stone and clay-slate are merely forms of clay that have undergone change from pressure or infiltrating solutions (see pp. 117, 121).

3. Volcanic Fragmental Rocks—Tuffs.

This section comprises all deposits which have resulted from the comminution of volcanic rocks. They thus include (1), those which consist of the fragmentary materials ejected from volcanic foci, or the true ashes and tuffs; and (2), some rocks derived from the superficial disintegration of already erupted and consolidated volcanic masses. Obviously the second series ought properly to be classed with the sandy or clayey rocks above described, since they have been formed in

[1] Ure's *Dict. Arts*, &c. ii. p. 142.

the same way. In practice, however, these detrital reconstructed rocks cannot always be certainly distinguished from those which have been formed by the consolidation of true volcanic dust and sand. Their chemical and lithological characters, both macroscopic and microscopic, are occasionally so similar, that their respective modes of origin have to be decided by other considerations, such as the occurrence of lapilli, bombs, slags in the truly volcanic series, and of well water-worn pebbles of volcanic rocks in the other. Attention to these features, however, usually enables the geologist to make the distinction, and to perceive that the number of instances where he may be in doubt is less than might be supposed. Only a comparatively small number of the rocks classed here are not true volcanic ejections.

Referring to the account of volcanic action in Book III. Part I., we may here merely define the use of the names by which the different kinds of ejected volcanic materials are known.

Volcanic Blocks.—Angular, sub-angular, round, or irregularly-shaped masses of lava several feet in diameter, sometimes of uniform texture throughout, as if they were large fragments dislodged by explosion from a previously consolidated rock, sometimes compact in the interior and cellular or slaggy outside.

Bombs.—Round, elliptical, or discoidal pieces of lava from a few inches up to one or more feet in diameter. They are frequently cellular internally, while the outer parts are fine grained. Occasionally they consist of a mere shell of lava with a hollow interior like a bomb-shell. Their mode of origin is explained at p. 206.

Lapilli (rapilli).—Ejected fragments of lava, round, angular, or indefinite in shape, varying in size from a pea to a walnut. Their mineralogical composition depends upon that of the lava from which they have been thrown up. Usually they are porous or finely vesicular in texture.

Volcanic Sand, Volcanic Ash.—The finer detritus erupted from volcanic orifices, consisting partly of rounded and angular fragments up to about the size of a pea, derived from the explosion of lava within eruptive vents, partly of vast quantities of microliths and crystals of some of the minerals of the lava. The finest dust is in a state of extremely minute subdivision. When examined under the microscope, it is sometimes found to consist not only of minute crystals and microliths, but of volcanic glass, which may be observed adhering to the microliths or crystals round which it flowed when still part of the fluid lava. The presence of minutely cellular fragments is characteristic of most volcanic fragmental rocks, and this structure may commonly be observed in the microscopic fragments and filaments of glass.

When these various materials are allowed to accumulate, they become consolidated and receive distinctive names. In cases where they fall into the sea or into lakes, they are liable at the outer margin of their area to be mingled with, and insensibly to pass into ordinary non-volcanic sediment. Hence we may expect to find transitional

varieties between rocks formed directly from the results of volcanic explosion and ordinary sedimentary deposits.

Volcanic Conglomerate.—A rock composed mainly or wholly of rounded or sub-angular fragments of any volcanic rocks in a paste derived chiefly or wholly from the same materials, usually exhibiting a stratified arrangement, and often found intercalated between successive sheets of lava. Conglomerates of this kind may have been formed by the accumulation of rounded materials ejected from volcanic vents; or as the result of the aqueous erosion of previously solidified lavas, or by a combination of both these processes. Well-rounded and smoothed stones almost certainly indicate long-continued water-action rather than trituration in a volcanic vent. In the Western Territories of the United States vast tracts of country are covered with masses of such conglomerate, sometimes 2000 feet thick. Captain Dutton has recently shown that similar deposits are in course of formation there now, merely by the influence of disintegration upon exposed lavas.[1]

Volcanic conglomerates receive different names according to the nature of the component fragments; thus we have *basalt-conglomerates*, where these fragments are wholly or mainly of basalt, *trachyte-conglomerates, porphyrite-conglomerates, phonolite-conglomerates*, &c.

Volcanic Breccia resembles volcanic conglomerate, except that the stones are angular. This angularity indicates an absence of aqueous erosion, and, under the circumstances in which it is found, usually points to immediately adjacent volcanic explosions. There is a great variety of breccias, as *basalt-breccia, diabase-breccia*, &c.

Volcanic Agglomerate.—A tumultuous assemblage of blocks of all sizes up to masses several yards in diameter, met with in the "necks" or pipes of old volcanic orifices. The stones and paste are commonly of one or more volcanic rocks, such as basalt or porphyrite, but they include also fragments of the surrounding rocks, whatever these may be, through which the volcanic orifice has been drilled. As a rule, agglomerate is devoid of stratification; but sometimes it includes portions which have a more or less distinct arrangement into beds of coarser and finer detritus, often placed on end, or inclined in different directions at high angles, as described in Book IV. Part VII.

Volcanic Tuff.—This general term may be made to include all the finer kinds of volcanic detritus, ranging on the one hand through coarse gravelly deposits into conglomerates, and on the other into exceedingly compact fine-grained rocks formed of the finest and most impalpable kind of volcanic dust. Some modern tuffs are full of microliths derived from the lava which was blown into dust. Others are formed of small rounded or angular grains of different lavas, with fragments of various rocks through which the volcanic funnels have been drilled. The tuffs of earlier geological periods have often been so much altered, that it is difficult to state what may have been their original condition. The absence of microliths and

[1] *High Plateaux of Utah*, p. 77.

glass in them is no proof that they are not true tuffs; for the presence of these bodies depends upon the nature of the lavas. If the latter were not vitreous and microlithic, neither would be the tuffs derived from them. In the Carboniferous volcanic area of Central Scotland the tuffs are made up of débris and blocks of the basaltic lavas, and, like these, are not microlithic, though in some places they abound in fragments of palagonite (Fig. 27).

Tuffs have consolidated sometimes under water, sometimes on dry land. As a rule they are distinctly stratified. Near the original vents of eruption they commonly present rapid alternations of finer and coarser detritus, indicative of successive phases of volcanic activity. They necessarily shade off into the sedimentary formations with which they were contemporaneous. Thus we have tuffs passing gradually into shale, limestone, sandstone, &c. The intermediate varieties have been called *ashy shale*, *tuffaceous shale*, or *shaley tuff*, &c. From the circumstances of their formation, tuffs frequently preserve the remains of plants and animals, both terrestrial and aquatic. Those of Monte Somma contain fragments of land plants and shells. Some of those of Carboniferous age in Central Scotland have yielded crinoids, brachiopods, and other marine shells. Like the other fragmentary volcanic rocks, the tuffs may be subdivided according to the nature of the lava from the disintegration of which they have been formed. Thus we have *felsite-tuffs*, *trachyte-*

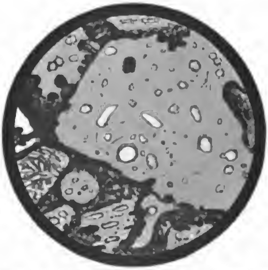

Fig. 27.—Microscopic Structure of Palagonite Tuff from Burntisland, Fife.

tuffs, *basalt-tuffs*, *pumice-tuffs*, *porphyrite-tuffs*, &c. A few varieties with special characteristics may be mentioned here.[1]

Trass.—A pale yellow or grey rock, rough to the feel, composed of an earthy or compact pumiceous dust, in which fragments of pumice, trachyte, greywacke, basalt, carbonized wood, &c., are imbedded. It has filled up some of the valleys of the Eifel, where it is largely quarried as a hydraulic mortar.

[1] On the occurrence and structure of tuffs, see J. C. Ward, *Q. J. Geol. Soc.* Geikie, *Trans. Roy. Soc. Edin.* xxix. Vogelsang, *Z. Deutsch. Geol. Ges.* xxiv. p. 543. Penck. *op. cit.* xxxi. p. 504. On the metamorphism of tuffs into lava-like rocks, see Dutton's *High Plateaux of Utah* (U. S. Geograph. and Geol. Survey of Rocky Mounts.), 1880, p. 79.

Peperino.—A dark brown earthy or granular tuff found in considerable quantity among the Alban Hills near Rome, and containing abundant crystals of augite, mica, leucite, magnetite, and fragments of crystalline limestone, basalt, and leucite-lava.

Palagonite-Tuff.—A bedded aggregate of dust and fragments of basaltic lava, among which are conspicuous angular pieces and minute granules of the pale yellow, green, red, or brown basic glass called palagonite. This vitreous substance is intimately related to the basalts. It appears to have gathered within volcanic vents and to have been emptied thence, not in streams, but by successive aeriform explosions, and to have been subsequently more or less altered. The percentage composition of a specimen from the typical locality, Palagonia, in the Val di Noto, Sicily, was estimated by S. von Waltershausen to be silica, 41·26; alumina, 8·60; ferric oxide, 25·32; lime, 5·59; magnesia, 4·84; potash, 0·54; soda, 1·06; water, 12·79. This rock is largely developed among the products of the Icelandic and Sicilian volcanoes; it occurs also in the Eifel and in Nassau. It has recently been found to be one of the characteristic features of tuffs of Carboniferous age in Central Scotland[1] (Fig. 27).

Schalstein.—Under this name German petrographers have placed a variety of rocks which consist of a green, grey, red, or mottled diabase-tuff impregnated with carbonate of lime and mixed with calcareous and argillaceous mud. They are interstratified with the Devonian formations of Nassau and the Harz, and with the Silurian rocks of Bohemia. They sometimes contain fragments of clay-slate, and are occasionally fossiliferous. They present amygdaloidal and porphyritic, as well as perfectly laminated structures. Probably they are in most cases true tuffs, but sometimes they may be forms of diabase-lavas, which, like the stratified formations in which they lie, have undergone alteration, and in particular have acquired a more or less distinctly fissile structure.[2]

4. Fragmental Rocks of Organic Origin.

This series includes deposits formed either by the growth and decay of organisms *in situ*, or by the transport and subsequent accumulation of their remains. These may be conveniently grouped, according to the predominant chemical ingredient, into Calcareous, Siliceous, Phosphatic, Carbonaceous, and Ferruginous.

(1.) Calcareous.

Besides the calcareous formations above described (p. 111) among the stratified crystalline rocks as resulting from the deposition of chemical precipitates, a still more important series is derived from

[1] *Trans. Roy. Soc. Edin.* xxix. p. 514.

[2] On some foliated igneous rocks in the "Killas" of Cornwall, see J. A. Phillips, *Q. J. Geol. Soc.* xxxii. p. 155, xxxiv. p. 471.

the remains of living organisms, either by growth on the spot or by transport and accumulation as mechanical sediment. To by far the larger part of the limestones intercalated in the rocky framework of our continents an organic origin may with probability be assigned. It is true, as has been above mentioned, that limestone, formed of the remains of animals or plants, is liable to an internal crystalline rearrangement, the effect of which is to obliterate the organic structure. Hence in many of the older limestones no trace of any fossils can be detected, and yet these rocks were almost certainly formed of organic remains. An attentive microscopic study of organic calcareous structures and of the mode of their replacement by crystalline calcite, affords, however, indications of former organisms, even in the midst of thoroughly crystalline materials.[1]

Limestone, composed of the remains of calcareous organisms, is found in layers which range from mere thin laminæ up to massive beds, several feet or even yards in thickness. In some instances, such as that of the Carboniferous or Mountain limestone of England and Ireland, and that of the Coal-measures in Wyoming and Utah, it occurs in continuous superposed beds to a united thickness of several thousand feet, and extends for hundreds of square miles, forming the rock out of which picturesque gorges, hills, and tablelands have been excavated.

Limestones of organic origin present every gradation of texture and structure, from mere soft calcareous mud or earth, evidently composed of entire or crumbled organisms up to solid compact crystalline rock, in which indications of an organic source can hardly be perceived. Mr. Sorby, in the address already cited, calls renewed attention to the importance of the form in which carbonate of lime is built up into animal structures. Quoting the opinion of Rose expressed in 1858, that the diversity in the state of preservation of different shells might be due to the fact that some of them had their lime as calcite, others as aragonite, he shows that this opinion is amply supported by microscopic examination. Even in the shells of a recent raised beach he observed that the inner aragonite layer of the common mussel had been completely removed, though the outer layer of calcite was well preserved. In some shelly limestones containing casts, the aragonite shells have alone disappeared, and where these still remain represented by a calcareous layer, this has no longer the original structure, but is more or less coarsely crystalline, being in fact a pseudomorph of calcite after aragonite and quite unlike contiguous calcite shells, which retain their original microscopical and optical characters.[2]

The following list comprises some of the more distinctive and important forms of organically derived limestones.

S h e l l - M a r l—a soft, white, earthy, or crumbling deposit formed

[1] Sorby, *Address to Geol. Society*, February, 1879.

[2] The student will find the address from which these citations are made full of suggestive matter in regard to the origin and subsequent history of limestones.

in lakes and ponds by the accumulation of the remains of shells and *Entomostraca* on the bottom. When such calcareous deposits become solid compact stone they are known as *fresh-water* (*lacustrine*) *limestones.* These are generally of a smooth texture, and either dull white or pale grey, their fracture slightly conchoidal, rarely splintery.

Calcareous (Foraminiferal) Ooze—a white or grey calcareous mud, of organic origin, found covering vast areas of the floor of the Atlantic and other oceans, and formed mostly of the remains of *Foraminifera,* particularly of forms of the genus *Globigerina.* Further account of this and other organic deep-sea deposits is given in Book III. Part II. Section iii.

FIG. 28.—FORAMINIFERAL (GLOBIGERINA) OOZE, DREDGED BY THE "CHALLENGER" EXPEDITION IN LAT. 50° 1′ S., LONG. 123° 4′ E., FROM A DEPTH OF 1800 FATHOMS, MAGNIFIED 50 DIAMETERS.

Shell sand—a deposit composed in great measure or wholly of comminuted shells, found commonly on a low shelving coast exposed to prevalent on-shore winds. When thrown above the reach of the waves and often wetted by rain, or by trickling runnels of water, it is apt to become consolidated into a mass, owing to the solution and redeposit of lime round the grains of shell (p. 155).

Coral-rock—a limestone formed by the continuous growth of coral-building polyps. This substance affords an excellent illustration of the way in which organic structure may be effaced from a limestone entirely formed from the remains of once living animals. Though the skeletons of the reef-building corals remain distinct on the upper surface, those of their predecessors beneath them are

gradually obliterated by the passage through them of percolating water dissolving and redepositing calcium carbonate. We can thus understand how a mass of crystalline limestone may have been produced from one formed out of organic remains without the action of any subterranean heat, but merely by the permeation of water from the surface.[1]

Chalk—a white soft rock, meagre to the touch, soiling the fingers, formed of a fine calcareous flour derived from the remains of *Foraminifera*, echinoderms, molluscs, and other marine organisms. By making thin slices of the rock and examining them under the microscope, Sorby has found that Foraminifera, particularly *Globigerina*, and single detached cells of comparatively shallow-water forms, probably constitute less than half of the rock by bulk (Fig. 14), the remainder consisting of detached prisms of the outer calcareous layer of *Inoceramus*, fragments of *Ostrea*, *Pecten*, echinoderms, spicules of sponges, &c. It is not quite like any known modern deep-sea deposit.

Crinoidal (Encrinite) Limestone—a rock composed in great part of crystalline joints of encrinites, with *Foraminifera*, corals, and molluscs. It varies in colour from white or pale grey, through shades of bluish-grey (sometimes yellow or brown, less commonly red) to a dark-grey or even black colour. It is abundant among Palæozoic formations, being in Western Europe especially characteristic of the lower part of the Carboniferous system.

(2.) Siliceous.

Silica is directly eliminated from both fresh and salt water by the vital growth of plants and animals. (Book III. Part II. Section iii.)

Diatom-earth (Infusorial earth)—a siliceous deposit formed chiefly of the frustules of diatoms, laid down both in salt and in fresh water. Wide areas of it are now being deposited on the bed of the South Pacific (*Diatom-ooze*, Fig. 173). In Virginia, United States, an extensive tract occurs covered with diatom-earth to a depth of 40 feet. It is used as *tripoli powder* for polishing purposes.

Radiolarian-ooze—an abysmal marine deposit consisting mainly of the remains of siliceous radiolarians and diatoms (Fig. 181). It is further referred to in Book III. Part II. Section iii.

Flint (Chert) has been already (p. 117) described, but should find a place also here from its evident connection with organic agency. It frequently encloses sponges, echini, shells, &c., and has evidently formed round these on the sea-floor, and has replaced their original calcium-carbonate. In some cases, as in the spicules of sponges, it has had a directly organic origin, having been secreted from sea-water by the living organisms; in other cases, where for example we find a calcareous shell, or echinus, or coral, converted into silica, it would seem that the substitution of silica for calcium-

[1] See Dana's *Coral and Coral Islands*, p. 354.

carbonate has been effected by a process of chemical pseudomorphism either after or during the formation of the limestone. The vertical ramifying masses of flint in chalk show that the calcareous ooze had to some extent accumulated before the segregation of these masses.[1]

(3.) Phosphatic.

A few invertebrata contain phosphate of lime. Among these may be mentioned the brachiopods *Lingula* and *Orbicula*,[2] also *Conularia*, *Serpulites*, and probably some crustacea. The shell of the recent *Lingula ovalis* was found by Hunt to contain, after calcination, 61 per cent. of fixed residue, which consisted of 85·70 per cent. of phosphate of lime; 11·75 carbonate of lime, and 2·80 magnesia. The bones of vertebrate animals likewise contain about 60 per cent. of phosphate of lime, while their excrement sometimes abounds in the same substance. Hence deposits rich in phosphate of lime have resulted from the accumulation of animal remains from Silurian times up to the present day. These certainly are far inferior in extent and importance to the calcareous, and even to the siliceous, formations, yet they are often of singular geological interest. The following examples may serve as illustrations.

Guano.—A deposit consisting mainly of the droppings of sea-fowl, formed on islands in rainless tracts off the western coasts of South America and of Africa. It is a brown, light, powdery substance with a peculiar ammoniacal odour. Analyses of American guano give —combustible organic matter and acids, 11·3; ammonia (carbonate, urate, &c.), 31·7; fixed alkaline salts, sulphates, phosphates, chlorides, &c., 8·1; phosphates of lime and magnesia, 22·5; oxalate of lime, 2·6; sand and earthy matter, 1·6; water, 22·2. This remarkable formation is highly valuable as a source of artificial manures. (Book III. Part II. Section iii.)

Bone-Breccia.—A deposit consisting largely of fragmentary bones of living or extinct mammalia, found sometimes under stalagmite on the floors of limestone caverns more or less mixed with earth, sand, or lime. In some older geological formations, bone-beds occur, formed largely of the remains of reptiles or fishes, as the "Lias bone-bed," and the "Ludlow bone-bed."

Coprolitic nodules and beds[3]—are formed of the accumulated excrement of vertebrated animals. Among the Carboniferous shales of the basin of the Firth of Forth, coprolitic nodules are abundant, together with the bones and scales of the larger ganoid fishes which voided them; abundance of broken scales and bones of the smaller

[1] On formation of chalk flints, see Wallich, *Q. J. Geol. Soc.* xxxvi. p. 68. Sollas, *Ann. Mag. Nat. Hist.* 1880. Hull and Hardman on Chert, *Trans. Roy. Dub. Soc.*, new series, vol. i. p. 71, 1878.

[2] Sterry Hunt, *Amer. Journ. Soc.* xvii. (1854), p. 236. Logan's *Geology of Canada*, 1863, p. 461.

[3] On the origin of phosphatic nodules and beds, see Gruner, *Bull. Soc. Géol. France*, xxviii. (2nd ser.) p. 62. Martin, *op. cit.* iii. 3rd sec. p. 273.

ganoids can usually be observed in the coprolites. Among the Lower Silurian rocks of Canada, numerous phosphatic nodules, supposed to be of coprolitic origin, occur.[1] Associated with the Bala limestone in the Lower Silurian series of North Wales is a band composed of concretions cemented in a black graphitic, slightly phosphatic, matrix, and containing usually 64 per cent. of phosphate of lime (phosphorite).[2] The tests of the trilobites and other organisms among the Cambrian rocks of Wales also contain phosphate of lime, sometimes to the extent of 20 per cent.[3] The phosphatic beds of the Cambridgeshire Cretaceous rocks are now largely worked as a source of artificial manure.

(4.) Carbonaceous.

The formations here included have almost always resulted from the decay and entombment of vegetation on the spot where it grew, sometimes by the drifting of the plants to a distance and their consolidation there. (See Book III. Part II. Section iii., LIFE.) In the latter case, they may be mingled with inorganic sediment, so as to pass into carbonaceous shale.

Peat.—Vegetable matter, more or less decomposed and chemically altered, found throughout temperate climates in boggy places where marshy plants grow and decay. It varies from a pale yellow or brown fibrous substance, like turf or compressed hay, in which the plant-remains are abundant and conspicuous, to a compact dark-brown or black material, resembling black clay when wet, and some varieties of lignite when dried. The nature and proportions of the constituent elements of peat, after being dried at 100° C., are illustrated by the analysis of an Irish example which gave—carbon, 60·48; hydrogen, 6·10; oxygen, 32·55; nitrogen, 0·88; while the ash was 3·30.

There is always a large proportion of water which cannot be driven off even by drying the peat. In the manufacture of compressed peat for fuel this constituent, which of course lessens the value of the peat as compared with an equal weight of coal, is driven off to a great extent by chopping the peat into fine pieces, and thereby exposing a large surface to evaporation. The ash varies in amount from less than 1·00 to more than 65 per cent., and consists of sand, clay, ferric oxide, sulphuric acid, and minute proportions of lime, soda, potash, and magnesia.[4]

Lignite (Brown coal).—Compact or earthy compressed and chemically altered vegetable matter, often retaining a lamellar or ligneous texture, with stems showing woody fibre crossing each other in

[1] *Geology of Canada*, p. 461.
[2] D. C. Davies. *Q. J. Geol. Soc.* xxxi. p. 357.
[3] Hicks, *op. cit.* p. 368.
[4] See Senft's *Humus- Marsch- Torf- und Limonit-bildungen*, Leipzig, 1862.

all directions. It varies from pale brown or yellow to deep brown or black. Some shade of brown is the usual colour, whence the name *brown coal*, by which it is often known. It contains from 55 to 75 per cent. of carbon, has a specific gravity of 0·5 to 1·5, burns easily to a light ash with a sooty flame and a strong burnt smell. It occurs in beds chiefly among the Tertiary strata, under conditions similar to those in which coal is found in older formations. It may be regarded as a stage in the alteration and mineralization of vegetable matter intermediate between peat and true coal.

Coal.—A compact usually brittle velvet black to pitch-black, iron-black, or dull, sometimes brownish rock, with a greyish black or brown streak, and in some varieties a distinctly cubical cleavage, in others a conchoidal fracture. It contains from 75 to 85 per cent. of carbon,

FIG. 29.—MICROSCOPIC STRUCTURE OF DALKEITH COAL, SHEWING LYCOPODIACEOUS SPORANGIA (MAGNIFIED 200 DIAMETERS).

has a specific gravity of 1·2—1·35, burns with comparative readiness, giving a clear flame, a strong aromatic or bituminous smell, some varieties fusing and caking into cinder, others burning away to a mere white or red ash.

In coal, though it consists of compressed vegetation, no trace of organic structure is usually apparent. An attentive examination, however, will often disclose portions of stems, leaves, &c., or at least of carbonized woody fibre. Some kinds are almost wholly made up of the spore-cases of lycopodiaceous plants. There is reason to believe that different varieties of coal may have arisen from original diversities in the nature of the vegetation out of which they were formed.

Coal occurs in seams or beds intercalated between strata of sandstone, shale, fireclay, &c., in geological formations of Palæozoic, Secondary, and Tertiary age. It should be remembered that the word coal is rather a popular than a scientific term, being indiscriminately applied to any mineral substance capable of being used as fuel. Strictly employed, it ought only to be used with reference to beds of fossilized vegetation, the result either of the growth of plants on the spot or of the drifting of them thither.

The following analyses show the chemical constituents in some of the principal varieties of coal:—

	Caking Coal.	Splint Coal.	Cannel Coal.	Anthracite.
Carbon	86·75	79·58	66·4	91·44
Hydrogen	5·24	5·50	7·54	3·46
Oxygen	6·61	8·33	10·84	2·58
Nitrogen		1·13	1·56	0·21
Earthy Substances .	1·40	5·46	13·82	2·31
Specific gravity . .	1·28	1·31	1·27	1·39

Anthracite—the most highly mineralized form of vegetation—is an iron-black to velvet-black substance, with a strong metalloidal to vitreous lustre, hard and brittle, containing over 90 per cent. of carbon, with a specific gravity of 1·35—1·7. It kindles with difficulty, and in a strong draught burns without fusing, smoking, or smelling, but giving out a great heat. It is a coal from which the bituminous parts have been eliminated. It occurs in beds like ordinary coal, but in positions where probably it has been subjected to some change whereby its volatile constituents have been expelled. It is found largely in South Wales, and sparingly in the Scottish Coal-fields, where the ordinary coal-seams have been approached by intrusive masses of igneous rock. It is largely developed in the great coal-field of Pennsylvania. Some Lower Silurian shales are black from diffused anthracite, and have in consequence led to fruitless searches for coal.

Oil-shale (*Brandschiefer*).—Shale containing such a proportion of hydrocarbons as to be capable of yielding mineral oil on slow distillation. This substance occurs as ordinary shales do, in layers or beds, interstratified with other aqueous deposits, as in the Scottish coal-fields. It is in a geological sense true shale, and owes its peculiarity to the quantity of vegetable (or animal) matter which has been preserved among its inorganic constituents. It consists of fissile argillaceous layers, highly impregnated with bituminous matter, passing on one side into common shale, on the other into cannel or parrot coal. The richer varieties yield from 30 to 40 gallons of crude oil to the ton of shale. They may be distinguished from non-bituminous or feebly bituminous shales (throughout the shale districts of Scotland) by the peculiarity that a thin paring curls up in front of the knife, and shows a brown lustrous streak. Some of the oil-shales in the Lothians are crowded with the valves of ostracod crustaceans, besides scales, coprolites, &c., of ganoid fishes. It is possible that the bituminous matter may in some cases have resulted from animal organisms, though the abundance of plant-remains indicates that it is probably in most cases of vegetable origin. Under the name "pyroschists" Sterry Hunt

classes the clays or shales (of all geological ages) which are hydrocarbonaceous, and yield by distillation volatile hydrocarbons, inflammable gas, &c.

Petroleum, a general term, under which is included a series of natural mineral oils. These are fluid hydrocarbon compounds, varying from a thin, colourless, watery liquidity to a black, opaque, tar-like viscidity, and in specific gravity from 0·8 to 1·1. The paler, more limpid varieties are generally called naphtha, the darker, more viscid kinds mineral tar, while the name petroleum, or rock-oil, has been more generally applied to the intermediate kinds.

Petroleum occurs sparingly in Europe. A few localities for it are known in Britain. It is found in large quantity along the country stretching from the Carpathians, through Gallicia and Moldavia, also at Baku on the Caspian. The most remarkable and abundant display of the substance, however, is in the so-called oil-regions of North America, particularly in Western Canada and Northern Pennsylvania, where vast quantities of it have been obtained in recent years. In Pennsylvania it is found especially in certain porous beds of sandstone or "sand-rocks," which occur as low down as the Old Red Sandstone, or even as the top of the Silurian system. In Canada it is largely present in still lower strata. Its origin in these ancient formations, where it cannot be satisfactorily connected with any destructive distillation of coal, is still an unsolved problem.[1]

Asphalt.—A smooth, brittle, pitch-like, black or brownish-black mineral, having a resinous lustre and conchoidal fracture, streak paler than surface of fracture, and specific gravity of 1·0 to 1·68. It melts at about the temperature of boiling water, and can be easily kindled, burning with a bituminous odour and a bright but smoky flame. It is composed chiefly of hydrocarbons, with variable admixture of oxygen and nitrogen. It occurs sometimes in association with petroleum, of which it may be considered a hardened oxidized form, sometimes as an impregnation filling the pores or chinks of rocks, sometimes in independent beds. In Britain it occurs as a product of the destructive distillation of coals and carbonaceous shales by intrusive igneous rocks, as at Binny Quarry, Linlithgowshire, but also in a number of places where its origin is not evident, as in the Cornish and Derbyshire mining districts, and among the dark flagstones of Caithness and Orkney, which are laden with fossil fishes. At Seyssel (Département de l'Aine) it forms a deposit 2500 feet long and 800 feet broad, which yields 1500 tons annually. It exudes in a liquid form from the ground round the borders of the Dead Sea. In Trinidad it forms a lake 1½ miles in circumference, which is cool and solid near the shore, but increases in temperature and softness towards the centre.

Graphite.—This mineral occurs in masses of sufficient size and

[1] See *Second Geol. Survey of Pennsylvania*, vol. ii. 1877. Also Ashburner, *Proc. Amer. Phil. Soc.* December, 1876.

importance to deserve a place in the enumeration of carbonaceous rocks. Its mineralogical characters have already (p. 63) been given. It occurs in distinct lenticular beds, and also diffused in minute scales, through slates, schists, and limestones of the older geological formations, as in Cumberland, Scotland, Canada, and Bohemia. It is likewise found occasionally as the result of the alteration of a coal seam by intrusive basalt, as at New Cummock in Ayrshire.

(5.) Ferruginous.

The decomposition of vegetable matter in marshy places and shallow lakes gives rise to certain organic acids, which, together with the carbonic acid so generally also present, decompose the ferruginous minerals of rocks and carry away soluble salts of iron. Exposure to the air leads to the rapid decomposition and oxidation of those solutions, which consequently give rise to precipitates, consisting partly of insoluble basic salts and partly of the hydrated ferric oxide. These precipitates mingled with clay, sand, or other mechanical impurity, and also with dead and decaying organisms, form deposits of iron-ore. Operations of this kind appear to have been in progress from a remote geological antiquity. Hence ironstones with traces of associated organic remains belong to many different geological formations, and are being formed still.[1]

Bog Iron-Ore (Lake ore, minérai des marais, Sumpferz).—A dark brown to black earthy but sometimes compact mixture of hydrated peroxide of iron, phosphate of iron, and hydrated oxide of manganese, frequently with clay, sand, and organic matter. An ordinary specimen yielded, peroxide of iron, 62·59; oxide of manganese, 8·52; sand, 11·37; phosphoric acid, 1·50; sulphuric acid, traces; water and organic matter, 16·02 = 100·00. Bog iron-ore may either be formed *in situ* from still water, or may be laid down by currents in lakes. Of the former mode of formation, a familiar illustration is furnished by the "moor-band pan" or hard ferruginous crust, which in boggy places and on some ill-drained land forms at the bottom of the soil on the top of a stiff and tolerably impervious subsoil. Abundant bog-iron or lake-ore is obtained from the bottoms of lakes in Norway and Sweden. It forms everywhere on the shallower slopes near banks of reeds, where there is no strong current of water, occurring in granular concretions that vary from the size of grains of coarse gunpowder up to nodules 6 inches in diameter, and forming layers 10 to 200 yards long, 5 to 15 yards broad, and 8 to 30 inches thick. These deposits are worked during winter by inserting perforated iron shovels through holes cut in the ice; and so rapidly do they accumulate, that instances are known where, after having been completely removed, the ore at the end of twenty-six years was

[1] See Senft, *op. cit.* p. 168; also *postea*, Book III. Part II. Section iii.

found to have gathered again to a thickness of several inches. According to Ehrenberg, the formation of bog-ore is due, not merely to the chemical actions arising from the decay of organic matter, but to a power possessed by diatoms of separating iron from water and depositing it as hydrous peroxide within their siliceous framework.

Aluminous Yellow Iron Ore is closely related to the foregoing. It is a mixture of yellow or pale brown hydrated peroxide of iron, with clay and sand, sometimes with silicate of iron, hydrated oxide of manganese, and carbonate of lime, and occurs in dull, usually pulverulent grains and nodules. Occasionally these nodules may be observed to consist of a shell of harder material, within which the yellow oxide becomes progressively softer towards the centre, which is sometimes quite empty. Such concretions are known as ætites or eagle-stones. This ore occurs in the Coal-measures of Saxony and Silesia, also in the Harz, Baden, Bavaria, &c., and among the Jurassic rocks in England.

Clay-Ironstone (Sphærosiderite) has been already (pp. 83, 116) referred to. It occurs abundantly in nodules and beds in the Carboniferous system in most parts of Europe. The nodules are generally oval and flattened in form, varying in size from a small bean up to concretions a foot or more in diameter. In many cases they contain in the centre some organic substance, such as a coprolite, fern, cone, shell, or fish, that has served as a surface round which the iron in the water and the surrounding mud could be precipitated. Seams of clay-ironstone vary in thickness from mere paper-like partings up to beds several feet deep. The Cleveland seam in the Middle Lias of Yorkshire is about 20 feet thick. In the Carboniferous system of Scotland certain seams known as *Blackband* contain from 10 to 52 per cent. of coaly matter, and admit of being calcined with the addition of little or no fuel. They are sometimes crowded with organic remains, especially lamellibranchs (*anthracosia, anthracomya,* &c.) and fishes (*rhizodus, megalichthys,* &c.).

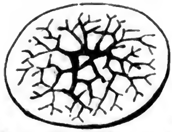

FIG. 30. — SEPTARIAN NODULE OF CLAY-IRONSTONE.

A microscopic examination of some black-band ironstones reveals a very perfect oolitic structure, showing that the iron has been precipitated in water having such a gentle movement as to keep the granules quietly moving while their successive concentric layers of carbonate were being deposited. Mr. Sorby has observed in the Cleveland ironstones an abnormal form of oolitic structure, and remarks that one specimen bore evidence that the iron, mostly in the form of small crystals of the carbonate, had been introduced subsequent to the formation of the rock, as it had replaced some of the aragonite of the enclosed shells.[1]

[1] Address to *Geol. Soc.* February, 1879.

The subjoined analyses show the composition of some varieties of clay ironstones.[1]

	Clay iron-ore (Coal measures), Yorkshire.	Black Band (Carboniferous), Scotland.	Cleveland ore (Lias), Yorkshire.
Peroxide of iron	1·45	2·72	2·86
Protoxide of iron	36·14	40·77	43·02
Protoxide of manganese	1·38	—	0·40
Alumina	6·74	—	5·87
Lime	2·70	0·90	5·14 zinc
Magnesia	2·17	0·72	5·21
Potash	0·65	—	—
Silica	17·37	10·10	7·17
Carbonic acid	26·57	26·41	25·50
Phosphoric acid	0·34	—	1·81
Sulphuric acid	trace	—	—
Iron pyrites	0·10	—	—
Water	1·77	1·0	3·48
Organic matter	2·40	17·38	0·15
	99·78	100·00	100·61
Percentage of iron	29 12	34·60	35·46

§ vii. Determination of Rocks.

Three methods of procedure are available in the examination and determination of rocks: 1st, the rough and ready but often sufficient appliances for examining macroscopic characters in the field or indoors; 2nd, microscopic investigation; 3rd, chemical analysis.

1. Macroscopic Examination in the field or indoors.

The instruments indispensable for the investigation of rocks in the field are few in number and simple in character and application. The observer will be sufficiently accoutred if he carries with him a hammer of such form and weight as will enable him to break off clean sharp unweathered chips from the edges of rock-masses, a small lens, a pocket-knife of hard steel for determining the hardness of rocks and minerals, a magnet or a magnetized knife-blade, and a small pocket phial of dilute hydrochloric acid.

Should the object be to form a collection of rocks, a hammer of at least three or four pounds in weight should be carried; also one or two chisels and a small trimming hammer, weighing about ¼ lb., for reducing the specimens to shape. A convenient size of specimens is $4 \times 3 \times 1$ inches. They should be as nearly as possible uniform in size, so as to be capable of orderly arrangement in the drawers or shelves of a case or cabinet. Attention should be paid not only to obtain a thoroughly fresh fracture of a rock, but also a weathered surface wherever there is anything characteristic in the weathering. Every specimen should have affixed to it a label indicating as exactly as

[1] See Percy's *Metallurgy*, vol. ii. Bischof. *Chem. und Phys. Geol.*, Supp. (1871) p. 65.

possible the locality from which it was taken. This information ought always to be written down in the field at the time of collecting, and should be wrapped up with the specimen, before it is consigned to the collecting bag. If, however, the student does not purpose to form a collection, but merely to obtain such chips as will enable him to judge of the characters of rocks, a hammer weighing from 1½ to 2 lbs. and of the shape indicated in Fig. 31 will be sufficient. The

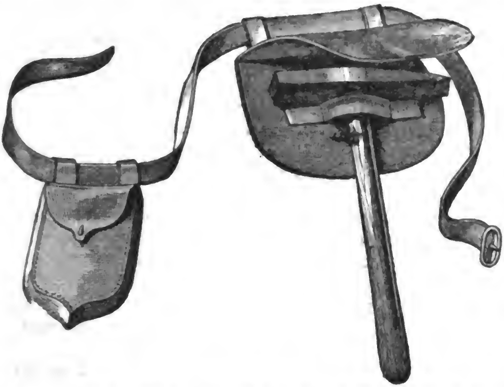

FIG. 31.—HAMMER, SHEATH, AND BELT, WITH LEATHER-CASE FOR HOLDING AZIMUTH COMPASS.

advantage of this form is that the hammer can be used not only for breaking hard stones, but also for splitting open shales and other fissile rocks, so that it unites the uses of hammer and chisel.

It is of course desirable that the learner should first acquire some knowledge of the nomenclature of rocks, by carefully studying a collection of correctly named and judiciously selected rock-specimens. Such collections may now be purchased at small cost from mineral dealers, or may be studied in the museums of most towns. Having accustomed his eye to the ordinary external characters of rocks, and become familiar with their names, he may proceed to determine them for himself in the field.

Finding himself face to face with a rock-mass, and after noting its geotectonic characters (Book IV.), the observer will proceed to examine the exposed or weathered surface. The earliest lesson he has to learn, and that of which perhaps he will in after life meet with the most varied illustrations, is the extent to which weathering conceals the true aspect of rocks. From what has been said in previous pages, the nature of the alterations will be understood, and further information regarding the chemical processes at work will be found in Book III. The practical study of rocks in the field soon

discloses the fact, that while in some cases the weathered crust so completely obscures the essential character of a rock that its true nature might not be suspected, in other instances it is the weathered crust that best reveals the real structure of the mass. Spheroidal crusts of a decomposing yellow ferruginous earthy substance, for example, would hardly be identified as a compact dark basalt, yet, on penetrating within these crusts, a central core of still undecomposed basalt may not unfrequently be discovered. Again, a block of limestone when broken open may present only a uniformly crystalline structure, yet if the weathered surface be examined, it will not improbably show many projecting fragments of shells, polyzoa, corals, crinoids, or other organisms. The really fossiliferous nature of an apparently unfossiliferous rock may thus be revealed by weathering. Many limestones also might from their fresh fracture be set down as tolerably pure carbonate of lime; but from the thick crust of yellow ochre on their weathered faces are seen to be highly ferruginous. Among crystalline rocks the weathered surface commonly throws light upon the mineral constitution of the mass, for some minerals decompose more rapidly than others, which are thus left isolated and more easily recognizable. In this manner the existence of quartz in many felspathic rocks may be detected. Its minute blebs or crystals, which to the naked eye or lens are lost among the brilliant facettes of the felspars, stand out amid the dull clay into which these minerals are decomposed.

The depth to which weathering extends should be noted. The student must not be too confident that he has reached its limit even when he comes to the solid more or less hard and splintery undecomposed stone. Granite sometimes decomposes into kaolin and sand to a depth of twenty or thirty feet. Limestones have often a mere film of crust, because their substance is almost entirely dissolved and removed by rain.

With some practice the inspection of a weathered surface will frequently suffice to determine the true nature and name of a rock. Should this preliminary examination, and a comparison of weathered and unweathered surfaces, fail to afford the information sought, we proceed to apply some of the simple and useful tests available for field-work. The lens will usually enable us to decide whether the rock is compact and apparently structureless, or crystalline, or fragmental. Having settled this point, we proceed to ascertain the hardness and colour of streak by scratching a fresh surface of the stone. A drop of weak acid placed upon the scratched surface or on the powder of the streak may reveal the presence of carbonic acid. By practice considerable facility can be acquired in approximately estimating the specific gravity of rocks merely by the hand. The following tables may be of assistance, but it must be understood at the outset that a knowledge of rocks can never be gained from instructions given in books, but must be acquired by actual handling and study of the rocks themselves.

i. A fresh fracture shows the rock to be close-grained, dull, with no distinct structure.

α. H. 0·5 or less up to 1; soft, crumbling or easily scratched with the knife, if not with the finger-nail; emits an earthy smell when breathed upon, does not effervesce with acid; is dark grey, brown, or blue, sometimes red, yellow, or even white = probably some clay rock, such as mudstone, massive shale, or fire-clay (p. 160); or a decomposed felspar rock like a close grained felsite or orthoclase porphyry. If the rock is hard and fissile it may be shale or clay-slate (pp. 121, 160).

β. H. 1·5—2. Occurs in beds or veins (sometimes fibrous), white, yellow, or reddish. Sp. gr. 2·2—2·4. Does not effervesce = probably gypsum (pp. 84, 115).

γ. Friable, crumbling, soils the fingers, white, or yellowish, brisk effervescence = chalk, marl, or some pulverulent form of limestone (pp. 111, 166).

δ. H. 3—4. Sp. gr. 2·5—2·7; pale to dark green or reddish, or with blotched and clouded mixtures of these colours. Streak white; feels soapy; no effervescence, splintery to subconchoidal fracture, edges subtranslucent. See serpentine (pp. 81, 152).

ε. H. averaging 3. Sp. gr. 2·6—2·8. White, but more frequently bluish-grey, also yellow, brown and black; streak white; gives brisk effervescence = some form of limestone (pp. 111–115, 165).

ζ. H. 3·5—4·5. Sp. gr. 2·8—2·95. Yellowish, white, or pale brown. Powder slowly soluble in acid with feeble effervescence, which becomes brisker when the acid is applied to the powder of the stone. See dolomite (pp. 83, 114).

η. H. 3—4. Sp. gr. 3—3·9. Dark brown to dull black, streak yellow to brown, feebly soluble in acid, which becomes yellow; occurs in nodules or beds, usually with shale; weathers with brown or blood-red crust = brown iron-ore. See also clay ironstone, (pp. 84, 116, 175); and limonite (pp. 116, 174); if the rock is reddish and gives a cherry-red streak, see hæmatite (pp. 67, 116).

θ. Sp. gr. 2·55. White, grey, yellowish, or bluish, rings under the hammer, frequently splits into thin plates, does not effervesce, weathered crust white and distinct = perhaps some compact variety of phonolite (p. 139. See also porphyrite p. 144).

ι. Sp. gr. 2·9—3·2. Black or dark green, weathered crust yellow or brown = probably some close-grained variety of basalt (p. 147), or aphanite (p. 143).

κ. H. 6—6·5, but less according to decomposition. Sp. gr. 2·55—2·7. Can with difficulty be scratched with the knife when fresh; White, bluish grey, yellow, lilac, brown, red; white streak; no effervescence = probably a felsitic rock (p. 136).

λ. H. 7. Sp. gr. 2·5—2·9. The knife leaves a metallic streak of steel upon the resisting surface. The rock is white, reddish, yellowish to brown or black, very finely granular or of a horny texture, gives no reaction with acid = probably silica in the form of a compact quartzite (p. 127), flint or calcedony (pp. 65, 117, 168).

ii. A fresh fracture shows the rock to be glassy.

Leaving out of account some glass-like but crystalline minerals such

as quartz and rock-salt, the number of vitreous rocks is comparatively small. The true nature of the mass in question will probably not be difficult to determine. It must be one of the volcanic rocks (p. 104). If it occurs in association with sanidine or siliceous lavas (liparites, trachytes) it will probably be obsidian (p. 140), or it may be pitchstone (p. 140); if it passes into one of the basalt-rocks, as so commonly happens along the edges of dykes and intrusive sheets, it is a glassy form of basalt (tachylite, hyalomelan, p. 149).

iii. A fresh structure shows the rock to be crystalline.

If the component crystals are sufficiently large for determination in the field, the name of the rock will readily be found. Where, however, they are too minute for identification even with a good lens, the observer may require to submit the rock to more precise investigation at home, before its true character can be ascertained. For the purposes of field-work, however, the following points should be noted.

a. The rock can be easily scratched with the knife.

(*a*) Effervesces briskly with acid = limestone.

(*b*) Powder of streak effervesces less briskly. See dolomite (pp. 83, 114).

(*c*) No effervescence with acid; may be granular crystalline gypsum (alabaster), or anhydrite (pp. 84, 115).

β. The rock is not easily scratched. It is almost certainly a silicate. Its character should be sought among the massive crystalline rocks (p. 129). If, for instance, it be heavy, appear to be composed of only one mineral, and have a marked greenish tint, it may be hornblende rock (p. 121); if it consist of some white mineral (felspar) and a green mineral which gives it a distinct green colour, while the weathered crust shows more or less distinct effervescence, it may be a fine grained diorite (p. 143), or diabase (p. 145); if it be grey and granular, with striated felspars and dark crystals (augite and magnetite), with a yellowish or brownish weathered crust, it is probably a dolerite (p. 148); if it be compact, finely-crystalline, scratched with difficulty, showing crystals of orthoclase, and with a bleached argillaceous weathered crust, it is probably an orthoclase-porphyry (p. 138), or quartz-porphyry (p. 135). The occurrence of distinct blebs or crystals of quartz in the fresh fractures or weathered face will suggest a place for the rock in the quartziferous cystalline series.

iv. A fresh fracture shows the rock to have a foliated structure.

The foliated rocks are for the most part easily recognizable by the prominence of their component minerals; their characters have been given at p. 118. Where the minerals are so intimately mingled as not to be separable by the use of the lens, the following hints may be of service:—

a. The rock has an unctuous feel, and is easily scratched. It may be talc-schist (p. 120), chlorite-schist (p. 121), hydrous mica-schist (p. 123), or foliated serpentine (p. 152).

β. The rock emits an earthy smell when breathed on, is harder than those included in *a*, is fine-grained and usually dark grey in colour, splits with a slaty fracture, and contains commonly scattered crystals of iron pyrites or some other mineral. It is some argillaceous-schist or clay-slate, the varieties of which

are named from the predominant enclosed mineral, as chiastolite-slate, andalusite-schist, ottrelite-schist, &c. (p. 121).

γ. The rock is composed of a mass of ray-like or fibrous crystals matted together. If the fibres are exceedingly fine, silky, and easily separable, it is probably asbestus; if they are coarser, greenish to white, glassy, and hard, it is probably an actinolite-schist (p. 121.)

δ. The rock has a hardness of nearly 7, and splits with some difficulty along micaceous folia. It is probably a quartzose variety of mica-schist, quartz-schist, or gneiss (pp. 120–128).

ε. The rock shows on its weathered surface small particles of quartz and folia of mica in a fine decomposing base. It is probably a fine-grained variety of mica-schist or gneiss.

v. A fresh fracture shows the rock to have a fragmental (clastic) structure.

Where the component fragments are large enough to be seen by the naked eye or with a lens, there is usually little difficulty in determining the true nature and proper name of the rock. Two characters require to be specially considered—the component fragments and the cementing paste.

1. *The Fragments.*—According to the shape, size, and composition of the fragments, different names are assigned to clastic rocks.

α. Shape.—If the fragments are chiefly rounded, the place of the rock may be sought in the sand and gravel series (p. 156), while if they are large and angular, it may be classed as a breccia (p. 157). Some mineral substances, however, do not acquire rounded outlines, even after long-continued attrition. Mica, for example, splits up into thin laminæ, which may be broken into small flakes or spangles, but never become rounded granules. Other minerals also which have a ready cleavage are apt to break up along their cleavage planes, and thus to retain angular contours. Calc-spar is a familiar example of this tendency. Organic remains composed of this mineral (such as crinoids and echinoids) may often be noticed in a very fragmentary condition, having evidently been subjected to long-continued comminution. Yet angular outlines and fresh or little worn cleavage surfaces may be found among them. Many limestones consist largely of sub-angular organic debris. Angular inorganic detritus is characteristic of volcanic breccias and tuffs (p. 161).

β. Size.—Where the fragments are hard rounded or sub-angular grains, the size of a pin's head or less, the rock is probably some form of sandstone (p. 158). Where they range up to the size of a pea, it may be a pebbly sandstone, fine conglomerate or grit; where they vary from the size of a pea to that of a walnut, it is an ordinary conglomerate; where they range up to the size of a man's head or larger, it is a coarse conglomerate. A considerable admixture of sub-angular stones makes it a brecciated conglomerate or breccia.

γ. Composition.—In the majority of cases the fragments are of quartz, or at least of some siliceous and enduring mineral. Sandstones consist chiefly of rounded quartz-grains (p. 155). Where these are unmixed with other ingredients, the rock is sometimes distinguished as a quartzose sandstone. Such a rock when indurated becomes quartzite (p. 126). Among the quartz grains, minute fragments of other minerals may be observed. When any one of these is prominent, it may give a name to the variety of sandstone, as felspathic, micaceous (p. 158). Vol-

canic tuffs and breccias are characterized by the occurrence of lapilli (very commonly *cellular*) of the lavas from the explosion of which they have been formed (p. 163). Among interbedded volcanic rocks the student will meet with beds which he may be at a loss whether to class as volcanic or as formed of ordinary sediment. They consist of an intermixture of volcanic detritus with sand or mud, and pass on the one side into true tuffs, on the other into sandstones, shales, limestones, &c. If the component fragments of a non-crystalline rock give a brisk effervescence with acid they are calcareous, and the rock (most likely a limestone, or at least a calcareous formation,) should be searched for traces of fossils.

2. *The Paste.*—It sometimes happens that the component fragments of a clastic rock cohere merely from pressure and without any discoverable matrix. This is occasionally the case with sandstone. Most commonly, however, there is some cementing paste. If a drop of weak acid produces effervescence from between the component non-calcareous grains of a rock, the paste is calcareous. If the grains are coated with a red crust which on being bruised between white paper gives a cherry-red powder, the cementing material is the anhydrous peroxide of iron. If the paste is yellow or brown, it is probably in great part the hydrous peroxide of iron. A dark brown or black matrix which can be dissipated by heating is bituminous. Where the component grains are so firmly cemented in an exceedingly hard matrix that they break across rather than separate from each other when the stone is fractured, the paste is probably siliceous.

ii. Microscopic Investigation.[1]

The value of the microscope as an aid in geological research has been sufficiently dwelt upon in the preceding pages. Some information may now be given as to the methods of procedure in microscopical inquiry.

1. Preparation of microscopic slides of rocks and minerals. —The observer ought to be able to prepare his own slices, and in many cases will find it of advantage to do so, or at least personally to superintend their preparation by others. It is desirable that he should know at the outset that no costly or unwieldy set of apparatus is needful for his purpose. If he is resident in one place and can accommodate a cutting machine, such as a lapidary's lathe, he will find the process of preparing rock-slices greatly facilitated.[2] The

[1] This section is taken, with alterations and additions, from the author's *Outlines of Field Geology.*

[2] A machine well adapted for both cutting and polishing was devised some years ago by Mr. J. B. Jordan, and may be had of Messrs. Cotton and Johnson, Grafton Street, Soho, London, for £10 10s. Another slicing and polishing machine, invented by Mr. F. G. Cuttell, 52 New Compton Street, Soho, London, costs £6 10s. These machines are too unwieldy to be carried about the country by a field-geologist. Fuess of Berlin supplies two small and convenient hand-instruments, one for slicing, the other for grinding and polishing. The slicing-machine is not quite so satisfactory for hard rocks as one of the larger more solid forms of apparatus worked by a treadle. But the grinding-machine is useful, and might be added to a geologist's outfit without material inconvenience. If a lapidary is within reach, much of the more irksome part of the work may be saved by getting him to cut off the thin slices in directions marked for him upon the specimens.

thickness of each slice must be mainly regulated by the nature of the rock, the rule being to make the slice as thin as can conveniently be cut, so as to save labour in grinding down afterwards. Perhaps the thickness of a shilling may be taken as a fair average. The operator, however, may still further reduce this thickness by cutting and polishing a face of the specimen, cementing that on glass in the way to be immediately described, and then cutting as close as possible to the cemented surface. The thin slice thus left on the glass can then be ground down with comparative ease.

Excellent rock-sections, however, may be prepared without any machine, provided the operator possesses ordinary neatness of hand and patience. He must procure as thin chips as possible. Should the rocks be accessible to him in the field, he should select the freshest portions of them, and by a dexterous use of the hammer break off from a sharp edge a number of thin splinters or chips, out of which he can choose one or more for rock-slices. These chips may be about an inch square. It is well to take several of them, as the first specimen may chance to be spoiled in the preparation. The geologist ought also always to carry off a piece of the same block from which his chip is taken, that he may have a specimen of the rock for future reference and comparison. Every such hand-specimen, as well as the chips belonging to it, ought to be wrapped up in paper on the spot where it is obtained, and with it should be placed a label containing the name of the locality and any notes that may be thought necessary. It can hardly be too frequently reiterated that all such field-notes ought as far as possible to be written down on the ground where the actual facts are before the eye for examination.

Having obtained his thin slices, either by having them slit with a machine or by detaching with a hammer as thin splinters as possible, the operator may proceed to the preparation of them for the microscope. For this purpose the following simple apparatus is all that is absolutely needful, though if a grinding-machine be added it will save time and labour.

List of Apparatus required in the Preparation of Thin Slices of Rocks and Minerals for Microscopical Examination.

1. A cast-iron plate ½ inch thick and 9 inches square.
2. Two pieces of plate-glass, 9 inches square.
3. A Water of Ayr stone, 6 inches long by 2½ inches broad.
4. Coarse emery (1 lb. or so at a time).
5. Fine or flour emery (ditto).
6. Putty powder (1 oz.).
7. Canada balsam. (There is an excellent kind prepared by Rimmington, Bradford, specially for microscopic preparations, and sold in shilling bottles.)
8. A small forceps, and a common sewing-needle with its head fixed in a short wooden handle.

9. Some oblong pieces of common flat window-glass; 2 × 1 inches is a convenient size.

10. Glasses with ground edges for mounting the slices upon. They may be had at any chemical instrument maker's in different sizes, the commonest in this country being 3 × 1 inches.

11. Thin covering-glasses, square or round. These are sold by the ounce; ¼ oz. will be sufficient to begin with.

12. A small bottle of spirits of wine.

The first part of the process consists in rubbing down and polishing one side of the chip or slice, if this has not already been done in cutting off a slice affixed to glass, as above mentioned. We place the chip upon the wheel of the grinding-machine, or, failing that, upon the iron plate, with a little coarse emery and water. If the chip is so shaped that it can be conveniently pressed by the finger against the plate and kept there in regular horizontal movement, we may proceed at once to rub it down. If, however, we find a difficulty, from its small size or otherwise, in holding the chip, one side of it may be fastened to the end of a bobbin or other convenient bit of wood by means of a cement formed of three-parts of rosin and one of bees-wax, which is easily softened by heating. A little practice will show that a slow, equable motion with a certain steady pressure is most effectual in producing the desired flatness of surface. When all the roughnesses have been removed, which can be told after the chip has been dipped in water so as to remove the mud and emery, we place the specimen upon the square of plate-glass, and with flour emery and water continue to rub it down until all the scratches caused by the coarse emery have been removed and a smooth polished surface has been produced.[1] Care should be taken to wash the chip entirely free of any grains of coarse emery before the polishing on glass is begun. It is desirable also to reserve the glass for polishing only. The emery gets finer and finer the longer it is used, so that by remaining on the plate it may be used many times in succession. Of course the glass itself is worn down, but by using alternately every portion of its surface and on both sides, one plate may be made to last a considerable time. If after drying and examining it carefully we find the surface of the chip to be polished and free from scratches, we may advance to the next part of the process. But it will often happen that the surface is still finely scratched. In this case we may place the chip upon the Water of Ayr stone and with a little water gently rub it to and fro. It should be held quite flat. The Water of Ayr stone too should not be allowed to get worn into a hollow, but should also be kept quite flat, otherwise we shall lose part of the chip. Some soft rocks, however, will not take an unscratched surface even with

[1] Exceedingly impalpable emery powder may be obtained by stirring some of the finest emery in water, and after the coarse particles have subsided, pouring off the liquid and allowing the fine suspended dust gradually to subside. Filtered and dried, the residue can be kept for the more delicate parts of the polishing.

the Water of Ayr stone. These may be finished with putty powder, applied with a bit of woollen rag.

The desired flatness and polish having been secured, and all trace of scratches and dirt having been completely removed, we proceed to a further stage, which consists in grinding down the opposite side and reducing the chip to the requisite degree of thinness. The first step is now to cement the polished surface of the chip to one of the pieces of common glass. A thin piece of iron (a common shovel does quite well) is heated over a fire, or is placed between two supports over a gas-flame.[1] On this plate must be laid the piece of glass to which the slice is to be affixed, together with the slice itself. A little Canada balsam is dropped on the centre of the glass and allowed to remain until it has acquired the necessary consistency. To test this condition, the point of a knife should be inserted into the balsam, and on being removed should be rapidly cooled by being pressed against some cold surface. If it soon becomes hard enough to resist the pressure of the finger nail, it has been sufficiently heated. Care, however, must be observed not to let it remain too long on the hot plate; for it will then become brittle and start from the glass at some future stage, or at least will break away from the edges of the chip and leave them exposed to the risk of being frayed off. The heat should be kept as moderate as possible, for if it becomes too great it may injure some portions of the rock. Chlorite, for example, is rendered quite opaque if the heat is so great as to drive off its water.

When the balsam is found to be ready, the chip, which has been warmed on the same plate, is lifted with the forceps, and laid gently down upon the balsam. It is well to let one end touch the balsam first, and then gradually to lower the other, as in this way the air is driven out. With the point of a needle or a knife the chip should be moved about a little, so as to expel any bubbles of air and promote a firm cohesion between the glass and the stone. The glass is now removed with the forceps from the plate and put upon the table, and a lead weight or other small heavy object is placed upon the chip, so as to keep it pressed down until the balsam has cooled and hardened. If the operation has been successful the slide ought to be ready for further treatment as soon as the balsam has become cold. If, however, the balsam is still soft, the glass must be again placed on the plate and gently heated, until on cooling, the balsam fulfils the condition of resisting the pressure of the finger-nail.

Having now produced a firm union of the chip and the glass, we proceed to rub down the remaining side of the stone with coarse emery on the iron plate as before. If the glass cannot be held in the hand or moved by the simple pressure of the fingers, which usually suffices, it may be fastened to the end of the bobbin with the

[1] A piece of wire-gauze placed over the flame, with an interval of an inch or more between it and the overlying thin iron plate, tends to diffuse the heat and prevent the balsam from being unequally heated.

cement as before. When the chip has been reduced until it is tolerably thin; until, for example, light appears through it when held between the eye and the window, we may, as before, wash it clear of the coarse emery and continue the reduction of it on the glass plate with fine emery. Crystalline rocks, such as granite, gneiss, diorite, dolerite, and modern lavas, can be thus reduced to the required thinness on the glass plate. Softer rocks may require gentle treatment with the Water of Ayr stone.

The last parts of the process are the most delicate of all. We desire to make the section as thin as possible, and for that purpose continue rubbing until after one final attempt we may perhaps find to our dismay that great part of the slice has disappeared. The utmost caution should be used. The slide should be kept as flat as possible, and looked at frequently, that the first indications of disruption may be detected. The thinness desirable or attainable depends in great measure upon the nature of the rock. Transparent minerals need not be so much reduced as more opaque ones. Some minerals, indeed, remain absolutely opaque to the last, like pyrite, magnetite, and ilmenite.

The slide is now ready for the microscope. It ought always to be examined with that instrument at this stage. We can thus see whether it is thin enough, and if any chemical tests are required they can readily be applied to the exposed surface of the slice. If the rock has proved to be very brittle, and we have only succeeded in procuring a thin slice after much labour and several failures, nothing further should be done with the preparation, unless to cover it with glass, as will be immediately explained, which not only protects it, but adds to its transparency. But where the slice is not so fragile, and will bear removal from its original rough scratched piece of glass, it should be transferred to one of the glass-slides (No. 10). For this purpose the preparation is once more placed on the warm iron plate, and close alongside of it is put one of the pieces of glass which has been carefully cleaned, and on the middle of which a little Canada balsam has been dropped. The heat gradually loosens the cohesion of the slice, which is then very gently pushed with the needle or knife along to the contiguous clean slip of glass. Considerable practice is needed in this part of the work, as the slice, being so thin, is apt to go to pieces in being transferred. A gentle inclination of the warm plate, so that a tendency may be given to the slice to slip downwards of itself on to the clean glass, may be advantageously given. We must never attempt to lift the slice. All shifting of its position should be performed with the point of the needle or other sharp instrument. If it goes to pieces we may yet be able to pilot the fragments to their resting-place on the balsam of the new glass, and the resulting slide may be sufficient for the required purpose.

When the slice has been safely conducted to the centre of the glass slip, we put a little Canada balsam over it, and warm it as before. Then taking one of the thin cover-glasses with the

forceps, we allow it gradually to rest upon the slice by letting down first one side, and then by degrees the whole. A few gentle circular movements of the cover-glass with the point of the needle or forceps may be needed to ensure the total disappearance of air-bubbles. When these do not appear, and when, as before, we find that the balsam has acquired the proper degree of consistence, the slide containing the slice is removed, and placed on the table with a small lead weight above it in the same way as already described. On becoming quite cold and hard the superabundant balsam round the edge of the cover-glass may be scraped off with a knife, and any which still adheres to the glass may be removed with a little spirits of wine. Small labels should be kept ready for affixing to the slides to mark localities and reference numbers. Thus labelled, the slide may be put away for future study and comparison.

The whole process seems perhaps a little tedious. But in reality much of it is so mechanical, that after the mode of manipulation has been learnt by a little experience, the rubbing-down may be done while the operator is reading. Thus in the evening, when enjoying a pleasant book after his day in the field, he may at the same time with some practice rub down his rock-chips, and thus get over the drudgery of the operation almost unconsciously.

Boxes with grooved sides for carrying microscopic slides are sold in different sizes. Such boxes are most convenient for a travelling equipage, as they go into small space, and with the help of a little cotton-wool they hold the glass-slides firmly without risk of breakage. For a final resting-place, a case with shallow trays or drawers in which the slides can lie flat is most convenient.

2. **The Microscope.**—Unless the observer proposes to enter into great detail in the investigation of the minuter parts of rock structure, he does not require to procure a large and expensive instrument. For most geological purposes objectives of $1\frac{1}{2}$, 1, and $\frac{1}{2}$ inch focal length with magnifying powers of from 30 to 70 diameters, are sufficient. But it is desirable also for special work, such as the investigation of crystallites and inclusions of minerals, to have an objective capable of magnifying up to 200 or 300 diameters. An instrument with fairly good glasses of these powers, according to the arrangement of object-glasses and eye-pieces, may be had of some London makers for £5. But for some of the most important parts of the microscopical study of rocks a rotating stage is requisite, the presence of which necessarily adds to the cost of the instrument. One of the best microscopes specially adapted for lithological research is that devised by Professor Rosenbusch, of which an English modification is made by Watson of Pall Mall, London, and sold at £21. It contains every apparatus required for ordinary work. A less complete but useful instrument is sold by the same maker for £9. 10s.

Among the indispensable adjuncts are two Nicol prisms, one to be fitted below the stage, the other most advantageously placed over

the eye-piece. A quartz-plate is useful in examination with polarized light. It should be arranged between the two Nicol prisms, either below the stage or in the tube above the objective, so as to be conveniently slipped in and out of the field as required. A nose-piece for two objectives screwed to the foot of the tube saves time and trouble by enabling the observer at once to pass from a low to a high power. The numerous pieces of apparatus necessary for physiological work are not needed in the examination of rocks and minerals.

3. **Methods of Examination.**—Examples of the nature of the kind of research practicable with the microscope in geology having already been abundantly given, a few hints may be here added for the guidance of the student in making his own microscopic observations.

Reflected Light.—It is not infrequently desirable to observe with the microscope the characters of a rock as an opaque object. This cannot usually be done with a broken fragment of the stone, except of course with very low powers. Hence one of the most useful preliminary examinations of a prepared slice is to place it in the field, and, throwing the mirror out of gear, to converge as strong a light upon it as can be had, short of bright direct sunlight. The advantage of this method is more particularly noticeable in the case of opaque minerals. The sulphides and iron oxides so abundant in rocks appear as densely black objects with transmitted light, and show only their external form. But by throwing a strong light upon their surface we may often discover not only their distinctive colours but their characteristic internal structure. Titaniferous iron is an admirable example of the advantage of this method. Seen with transmitted light that mineral appears in black, utterly structureless grains or opaque patches though frequently bounded by definite lines and angles. But with reflected light the cleavage and lines of growth of the mineral can then often be clearly seen, and what seemed to be uniform black patches are found in many cases to enclose bright brassy kernels of pyrite. Magnetite also presents a characteristic blue-black colour, which distinguishes it from the other iron oxides.

Transmitted Light.—It is, of course, with the light allowed to pass through prepared slices that most of the microscopic examination of minerals and rocks is performed. A little experience will show the learner that in viewing objects in this way he may obtain somewhat different results from two slices of the same rock according to their relative thinness. In the thicker one a certain mineral or rock, obsidian for example, will appear perhaps brown or almost black, while in the other what is evidently the same mineral may be pale yellow, green, brown, or almost colourless. Triclinic felspars seen in polarized light give only a pale milky light when extremely thin, but present bright chromatic bands when somewhat thicker.

Polarized Light.—By means of polarized light an exceedingly delicate method of investigation is made available. We use both

the Nicol prisms. If the object be singly refracting, such as a piece of glass, or an amorphous body, or a crystal belonging to some substance which crystallizes in the isometric or cubic system, the light will reach our eye apparently unaffected by the intervention of the object. The field will remain dark when the axes of the two prisms are at right angles (crossed Nicols), in the same way as if no intervening object were there. Such bodies are *isotropic*. If, however, the substance under examination be doubly refracting—a mineral belonging to one of the other crystallographic systems—it will modify the polarized beam of light. On rotating one of the prisms we now perceive bands or flashes of colour, and numerous lines appear which before were invisible. The field no longer remains dark when the two Nicol prisms are crossed. Such a substance is *anisotropic*.

It is evident, therefore, that we may readily tell by this means whether or not a rock contains any glassy constituent. If it does, then that portion of its mass will become dark when the prisms are crossed, while the crystalline parts which in the vast majority of cases do not belong to the cubic system, will remain conspicuous by their brightness. A thin plate of quartz makes this separation of the glassy and crystalline parts of a rock even more satisfactory. It is placed between the Nicol prisms, which may be so adjusted with reference to it that the field of the microscope appears uniformly violet. The glassy portion of any rock, being singly refracting or isotropic, placed on the stage will allow the violet light to pass through unchanged, but the crystalline portions, being doubly refracting or anisotropic, will alter the violet light into other prismatic colours. The object should be rotated in the field and the eye should be kept steadily fixed pon one portion of the slide at a time, so that any change may be observed. This is an extremely delicate test for the presence of glassy and crystalline constituents.

In searching for the crystallographic system to which a mineral in a microscopic slice should be referred, attention is given to the directions in which the mineral appears dark, in other words, to the directions of its extinction, between crossed Nicols. It is extinguished when two of its axes of elasticity for vibrations of light coincide with the principal sections of the two prisms. During a complete rotation of the slide in the field of the microscope the mineral becomes dark in four positions, each of which marks that coincidence. When on the other hand the prisms are placed parallel to each other, the coincidence of their principal sections with the axes of elasticity in the mineral allows the maximum of light to pass through, which likewise occurs four times in a complete rotation of the mineral. The different crystallographic systems are distinguishable by the relation between their crystallographic axes and their axes of elasticity. By noting this relation in the case of any given mineral (and there are usually sections enough of each mineral in the same rock-slice to furnish the required data) its crystalline system may be fixed. But in many

cases it has been found possible to establish characteristic distinctions for individual mineral species, by noting the angle between the direction of their extinction and certain principal faces. It would be beyond the scope of this volume to enter into the details of this subject, which must be sought in some of the works already cited. The publications of Zirkel, Rosenbusch, von Lasaulx, Fouqué and Michel-Lévy may especially be consulted.

Pleochroism (*Dichroism*).—Some minerals show a change of colour when a Nicol prism is rotated below them, hornblende, for example, exhibiting a gradation from deep brown to dark yellow. A mineral presenting this change is said to be pleochroic (polychroic, dichroic, trichroic). To ascertain the pleochroism of any mineral we may remove the upper polarizing prism and leave only the lower. If, as we rotate the latter directly under the stage of the microscope, no change of tint can be observed, there is no pleochroic mineral present, or at least none which shows pleochroism at the angle at which it has been bisected in the slice. But we may often detect in a slice of some crystalline rock little crystals which offer a change of hue as the prism goes round. These are examples of pleochroism. This behaviour may be used to detect the mineral constituents of rocks. Thus the two minerals hornblende and augite, which in so many respects resemble each other, cannot always be distinguished by cleavage angles, in microscopic slices. But as Tschermak pointed out, augite remains passive or nearly so as the lower prism is rotated: it is not pleochroic, or only very feebly so; while hornblende, on the other hand, especially in its dark varieties, is usually strongly pleochroic. It is to be observed, however, that the same mineral is not always equally pleochroic, and that the absence of this property is therefore not so reliable as a negative test, as its presence is as a positive test.

In his examination of rocks with the microscope the student may find an advantage in propounding to himself the following questions, and referring to the previous pages here cited.

1st, Is the rock entirely crystalline (p. 105) consisting solely of crystals of different minerals interlaced; and if so, what are these minerals? 2nd, Is there any trace of a glassy ground-mass or base (p. 99)? Should this be detected, the rock is certainly of volcanic origin (p. 104). 3rd, Can any evidence be found of the devitrification of what may have been at one time the glassy basis of the whole rock? This devitrification might be shown by the appearance of numerous microscopic hairs, rods, bundles of feather-like irregular or granular aggregations (p. 100). 4th, In what order did the minerals crystallize? This may often be very clearly made out with the microscope, as, for instance, where one mineral is enclosed within another (p. 99). 5th, What is the nature of any alteration which the rock may have undergone? In a vast number of cases the slices show abundant evidence of such metamorphism; felspar passing into granular kaolin, augite changing into

viridite, olivine into serpentine, while secondary calcite, quartz, and zeolites run in minute veins or fill up insterstices of the rock (p. 107). 6th, Is the rock a fragmental one; and if so, what is the nature of its component grains? (p. 105.) Is any trace of organic remains to be detected? (p. 106.)

iii. Chemical Analysis.[1]

The determination of the chemical composition of rocks by detailed analysis in the wet way, demands an acquaintance with practical chemistry, which comparatively few geologists possess, and is consequently for the most part left in the hands of chemists, who are not geologists. But as some theoretical questions in geology involve a considerable knowledge of chemical processes, so a satisfactory analysis of rocks is best performed by one who understands the nature of the geological problems, on which such an analysis may be expected to throw light. As a rule, detailed chemical analysis lies out of the sphere of a geologist's work; yet the wider his knowledge of chemical laws and methods the better. He should at least be able to employ with accuracy the simpler processes of chemical research, to some of which reference has already been frequently made.

1. *Pulverization.*—Much may be learnt regarding the composition of a rock by reducing it to powder. This may be roughly done by placing some pieces of the rock within folds of paper upon a surface of steel, and reducing them to powder by a few smart blows of a hammer. But a steel mortar is more serviceable. The powder can be sifted through sieves of varying degrees of fineness and the separate fragments may be examined with a lens. If they are dark in colour they may be placed on white paper, if light-coloured they are more readily observed upon a black paper. Portions of this powder may be carefully washed and mounted with Canada balsam on glass, as in the way already described for thin slices. Magnetic particles may be extracted with a magnet, the end of which is preserved from contact with the powder by being covered with fine tissue-paper. An electro-magnet will at once withdraw the particles of minerals which contain far too little iron to be ordinarily recognized as magnetic; in this way the particles of a ferruginous magnesian mica may in a few seconds be gathered out of the powder of a granite.

2. *Treatment with Acid.*—The geologist's accoutrements for the field should include a small acid-bottle with a glass stopper prolonged downwards into a point. Dilute hydrochloric acid is commonly employed. When a drop of this acid gives effervescence upon a surface of rock, the reaction is caused by the liberation of bubbles of carbon dioxide, as this oxide is replaced by the more powerful acid. Hence effervescence is an indication of the presence of carbonates, and when brisk is specially characteristic of calcium carbonate. Lime-

[1] Taken, with some alterations and additions, from the author's *Outlines of Field Geology*.

stone and markedly calcareous rocks may thus at once be detected. By the same means the decomposition of such rocks as dolerite may be traced to a considerable distance inward from the surface; the original lime-bearing silicate of the rock having been decomposed by infiltrating rain water, and partially converted into carbonate of lime. This carbonate being far more sensitive to the acid test than the other carbonates usually to be met with among rocks, a drop of weak cold acid suffices to produce abundant effervescence even from a crystalline face. But the effervescence becomes much more marked if we apply the acid to the powder of the stone. For this purpose a scratch may be made and then touched with acid, when a copious discharge of carbonic acid may be obtained where otherwise it might appear so feebly as perhaps even to escape observation. Some carbonates, dolomite for example, are hardly affected by acid until powdered. In other cases the acid requires to be heated, or must be used very strong, as with siderite.

It is a convenient method of roughly estimating the purity of a limestone to place a fragment of the rock in hydrochloric acid. If there is much impurity (clay, sand, oxide of iron, &c.), this will remain behind as an insoluble residue, and may then be further tested chemically or examined with the microscope. Of course the acid may attack some of the impurities, so that it cannot be concluded that the residue absolutely represents everything present in the rock except the carbonate of lime, but the proportion of non-calcareous matter so dissolved by the acid will usually be small.

Hydrofluoric acid is a reagent of considerable service in separating the mineral constituents of rocks. The rock to be studied is reduced to powder and introduced gently into a platinum capsule containing the concentrated acid. During the consequent effervesence the mixture is cautiously stirred with a platinum spatula. Some minerals are converted into fluorides, others into fluosilicates, while some, particularly the iron-magnesia species, remain undissolved. The thick jelly of silica and alumina is removed with water, and the crystalline minerals lying at the bottom can then be dried and examined. By arresting the solution at different stages the different minerals may be isolated. This process is admirably adapted for collecting the pyroxene of pyroxenic rocks.[1]

3. *Further chemical processes.*—A thorough chemical analysis of a rock or mineral is indispensable for the elucidation of its composition. But there are several processes by which, until that complete analysis has been made, the geologist may add to his knowledge of the chemical nature of the objects of his study. It is commonly the case that minerals about which he may be doubtful are precisely those which, from their small size, are most difficult of separation from the rest of the rock preparatory to analytical processes. The mineral apatite, for example, occurs in minute hexagonal prisms which on cross-fracture might be mistaken for nepheline,

[1] Fouqué et Michel-Lévy, *op. cit.* p. 116.

or even sometimes for quartz. If, however, a drop of solution of molybdate of ammonia be placed upon one of these crystals, a yellow precipitate will appear if it be apatite. Nepheline, which is another hexagonal mineral likewise abundant in some rocks, gives no yellow precipitate with the ammonia solution, while if a drop of hydrochloric acid be put over it crystals of chloride of sodium or common salt will be obtained. These reactions can be observed even with minute crystals, by placing them under the microscope and using an exceedingly attenuated pipette for dropping the liquid on the slide.

Recently two ingenious applications of chemical processes to the determination of minute fragments of minerals have been made. In one of these, devised by Boricky,[1] hydrofluosilicic acid of extreme purity is employed. This acid decomposes most silicates, and forms from their bases hydrofluosilicates. A particle about the size of a pin-head of the mineral to be examined is fixed by its base upon a thin layer of Canada balsam spread upon a slip of glass, and a drop of the acid is placed upon it. The preparation is then set in moist air near a saucer of water under a bell-glass for twenty-four hours, after which it is enclosed in dry air, with chloride of calcium. In a few hours the hydrofluosilicates crystallize out upon the balsam and can be examined with the microscope. Those of potassium take the form of cubes, of sodium hexagonal prisms, &c.

The second process consists in utilizing the colorations given to the flame of a Bunsen burner by sodium and potassium. An elongated splinter of the mineral to be examined is first placed in the outer or oxidizing part of the flame near the base, and then in the reducing part further up and nearer the centre. The amount of sodium present in the mineral is indicated by the extent to which the flame is coloured yellow. The potassium is similarly estimated, but the flame is then looked at with cobalt glass, so as to eliminate the influence of the sodium.[2]

Another process has been devised by M. Thoulet for making a qualitative and even quantitative analysis of the powder of a rock. It consists in the use of a solution of iodide of mercury in iodide of potassium, which at a temperature of 11° C. has a density of 2·77. The powder of a rock being introduced into this liquid, those particles whose specific gravity exceeds that of the liquid will sink to the bottom, while those which are lighter will float. This process allows of the separation of the felspars from each other, and at once eliminates the heavy minerals such as hornblende, augite, and black mica.[3]

4. *Blow-pipe Tests.*—The chemical tests with the blow-pipe are simple, easily applied, and require only patience and practice to give great assistance in the determination of minerals. If unacquainted

[1] *Archiv Naturwiss. Landesdurchforschung von Böhmen*, iii. fasc. 3, 1876.

[2] Szabo, "Ueber eine neue Methode die Felspathe auch in Gesteinen zu bestimmen." Buda-Pest, 1876.

[3] Fouqué et Michel-Lévy, *op. cit.* p. 117.

with blow-pipe analysis the student must refer to one or other of the numerous text-books on the subject, some of which are mentioned below.[1] For early practice the following apparatus will be found sufficient:—

1. Blow-pipe.
2. Thick-wicked candle, or a tin box filled with the material of Child's night-lights, and furnished with a piece of Freyberg wick in a metallic support.
3. Platinum-tipped forceps.
4. A few pieces of platinum wire in lengths of three or four inches.
5. A few pieces of platinum foil.
6. Some pieces of charcoal.
7. A number of closed and open tubes of hard glass.
8. Three small stoppered bottles containing sodium carbonate, borax, and microcosmic salt.
9. Magnet.

This list can be increased as experience is gained. The whole apparatus may easily be packed into a box which will go into the corner of a portmanteau.

[1] The great work on the blow-pipe is Plattner's, of which an English translation has been published. Elderhorst's *Manual of Qualitative Blow-pipe Analysis and Determinative Mineralogy*, by H. B. Nason and C. F. Chandler (Philadelphia: N. S. Porter and Coates), is a smaller but useful volume; while still less pretending is Scheerer's *Introduction to the Use of the Mouth Blow-pipe*, of which a third edition by H. F. Blanford was published in 1875 by F. Norgate. An admirable work of reference will be found in Professor Brush's *Manual of Determinative Mineralogy* (New York: J. Wiley and Son).

The student who would pursue physical geology by original research in the field and abroad may consult Boué, "Guide du Géologue Voyageur," 2 vols. 1835; Élie de Beaumont, "Leçons de Géologie pratique," vol. I., 1845; Penning and Jukes-Browne, "Field Geology," 2nd edit. 1880; A. Geikie, "Outlines of Field Geology," 1879.

BOOK III.

DYNAMICAL GEOLOGY.

Dynamical geology investigates the processes of change at present in progress upon the earth, whereby modifications are made on the structure and composition of the crust, on the relations between the interior and the surface, as shown by volcanoes, earthquakes, and other terrestrial disturbances, on the distribution of land and sea, on the outlines of the land, on the form and depth of the sea-bottom, on marine currents, and on climate. Bringing before us, in short, the whole range of geological activities, it leads us to precise notions regarding their relations to each other, and the results which they achieve. A knowledge of this branch of the subject is thus the essential groundwork of a true and fruitful acquaintance with the principles of geology, seeing that by the study of the present order of nature, it provides a key for the interpretation of the past.

The whole range of operations in Dynamical Geology may be regarded as a vast cycle of change, into the investigation of which the student may break at any point, and round which he may travel, only to find himself brought back to his starting-point. It is a matter of comparatively small moment at what part of the cycle the inquiry is begun. The changes seen in action will always be found to have resulted from some that preceded, and to give place to others that follow them.

At an early time in the earth's history, anterior to any of the periods of which a record remains in the visible rocks, the chief sources of geological action probably lay within the earth itself. The planet still retained much of its initial heat, and in all likelihood was the theatre of great chemical changes. As the outer layers of the globe cooled, and the disturbances due to internal heat and chemical action became less marked, the influence of the sun, which must always have operated, and which in early geological times may have been more effective than it afterwards became, would then stand out more clearly, giving rise to that wide circle of superficial changes wherein variations of temperature and the circulation of air and water over the surface of the earth come into play.

In the pursuit of his inquiries into the past history and into the present *régime* of the earth, the student must needs keep his mind

ever open to the reception of evidence for kinds and especially for degrees of action which he had not before encountered. Human experience has been too short to allow him to assume that all the causes and modes of geological change have been definitively ascertained. Besides the fact that both terrestrial and solar energy were once probably more intense than now, there may remain for future discovery evidence of former operations by heat, magnetism, chemical change, or other agency, that may explain phenomena with which geology has to deal. Of the influences, so many and profound, which the sun exerts upon our planet, we can as yet only perceive a little. Nor can we tell what other cosmical influences may have lent their aid in the revolutions of geology.

In the present state of knowledge, all the geological energy upon and within the earth must ultimately be traced back to the primeval energy of the parent nebula, or sun. There is, however, a certain propriety and convenience in distinguishing between that part of it which is due to the survival of some of the original energy of the planet, and that part which arises from the present supply of energy received day by day from the sun. In the former case the geologist has to deal with the interior of the earth and its reaction upon the surface; in the latter he is called upon to study the surface of the earth, and to some extent its reaction on the interior. This distinction allows of a broad treatment of the subject under two divisions:—

I. Hypogene or Plutonic Action—the changes within the earth caused by original internal heat and by chemical action.

II. Epigene or Surface Action—the changes produced on the superficial parts of the earth, chiefly by the circulation of air and water set in motion by the sun's heat.

Part I. Hypogene Action.

An Inquiry into the Geological Changes in Progress beneath the Surface of the Earth.

In the discussion of this branch of the subject it is useful to carry in the mind the conception of a globe still intensely hot within, radiating heat into space, and consequently contracting in bulk. Portions of molten rocks from inside are from time to time poured out at the surface. Sudden shocks are generated by which destructive earthquakes are propagated to and along the surface. Wide geographical areas are upraised or depressed. In the midst of these movements the rocks of the crust are shattered, fractured, squeezed, crumpled, rendered crystalline, and even fused.

Section I. Volcanoes and Volcanic action.[1]

§ 1. Volcanic Products.

The term volcanic action (vulcanism or vulcanicity) embraces all the phenomena connected with the expulsion of heated materials from the interior of the earth to the surface. Among these phenomena some possess an evanescent character, while others leave permanent proofs of their existence. It is naturally to the latter that the geologist gives chief attention, for it is by their means that he can trace former phases of volcanic activity in regions where, for many ages, there have been no volcanic eruptions. In the operations of existing volcanoes he can observe only superficial manifestations of volcanic action. But, examining the rocks of the earth's crust, he discovers that amid the many terrestrial revolutions which geology reveals, the very roots of former volcanoes have been laid bare, displaying subterranean phases of vulcanism which could not be studied in any modern volcano. Hence an acquaintance only with active volcanoes will not afford a complete knowledge of volcanic action. It must be supplemented and enlarged by an investigation of the traces of ancient volcanoes preserved in the crust of the earth. (Book IV. Part VII.)

The word "volcano" is applied to a conical hill or mountain, (composed mainly or wholly of erupted materials) from the summit, and often also from the sides of which hot vapours issue, and ashes and streams of molten rock are intermittently expelled. The term "volcanic" designates all the phenomena essentially connected with one of these channels of communication between the surface and the heated interior of the globe. Yet there is good reason to believe that the active volcanoes of the present day do not afford by any means a complete type of volcanic action. The first effort in the formation of a new volcano is to establish a fissure in the earth's crust. A volcano is only one vent or group of vents established along the line of such a fissure. But in many parts of the earth, alike in the old world and the new, there have been periods in the earth's history when the crust was rent into innumerable fissures

[1] The student is referred to the following works in which the phenomena of volcanoes are specially described. Scrope, "Considerations on Volcanoes," London, 1825; "Volcanoes," London, 2nd edit. 1872; "Extinct Volcanoes of Central France," London, 1858; "On Volcanic Cones and Craters," *Quart. Journ. Geol. Soc.* 1859. Daubeny, "A Description of Active and Extinct Volcanoes," 2nd edit., London, 1858. Darwin, "Geological Observations on Volcanic Islands," 2nd edit., London, 1876. A. von Humboldt, "Ueber den Bau und die Wirkung der Vulkane," Berlin, 1824. L. von Buch, "Ueber die Natur der vulkanischen Erscheinungen auf den Canarischen Inseln," *Poggend. Annalen* (1827), ix. x.; "Ueber Erhebungskratere und Vulkane," *Poggend. Annalen* (1836), xxxvii. E. A. von Hoff, "Geschichte der durch Ueberlieferung nachgewiesenen natürlichen Veränderungen der Erdoberfläche," (Part ii., "Vulkane und Erdbeben,") Gotha, 1824. C. W. C. Fuchs, "Die vulkanischen Erscheinungen der Erde," Leipzig, 1865. R. Mallet, "On Volcanic Energy," *Phil. Trans.* 1873. E. Reyer, "Beitrag zur Physik der Eruptionen," Vienna, 1877. Fouqué, "Santorin et ses éruptions," Paris, 1879. References will be found in succeeding pages to other and more special memoirs.

over areas thousands of square miles in extent, and when the molten rock, instead of issuing, as it does at a modern volcano, in narrow streams from one or more points, welled out from the rents, and flooded enormous tracts of country without forming any mountain or volcano in the usual sense of these terms. Of these "fissure-eruptions," apart from volcanic cones, no examples have occurred within the times of human history, unless some of the lava-floods of Iceland can be so regarded. They can only be studied from the remains of former convulsions. Their importance, however, has not yet been generally recognised in Europe, though acknowledged in America, where they have been largely developed. Much still remains to be done before their mechanism is as well understood as that of the lesser type to which all present volcanic action belongs. Hence in the succeeding narrative an account is first given of the ordinary and familiar volcano and its products; and in § 3 ii., some details are given of the general aspect and character of the more gigantic fissure eruptions.

The openings by which heated materials from the interior now reach the surface include volcanoes (with their various accompanying orifices) and hot-springs.

The prevailing conical form of a volcano is that which the ejected materials naturally assume round the vent of eruption. The summit of the cone is truncated (Fig. 32) and presents a cup-shaped or cauldron-like cavity termed the crater, at the bottom of which is the top of the main funnel or pipe of communication with the heated interior. A volcano, when of small size, may consist merely of one cone; when of the largest dimensions, it forms a huge mountain, with many subsidiary cones and many lateral fissures or pipes, from which the heated volcanic products are given out. Mount Etna (Fig. 32) rising from the sea to a height of 10,840 feet, and supporting as it does some 200 minor cones, many of which are in themselves considerable hills, is a magnificent example of a colossal volcano.

The materials erupted from volcanic vents may be classed as (1) gases and vapours, (2) water, (3) lavas, (4) fragmentary substances. A brief summary under each of these heads may be given here; the share taken by the several products in the phenomena of an active volcano is described in § 2.

1. **Gases and Vapours** exist absorbed in the molten magma within the earth's crust. They play an important part in volcanic activity, showing themselves in the earliest stages of a volcano's history, and continuing to appear for centuries after all the other evidences of subterranean action have ceased to be manifested. By much the most abundant of them all is *steam*, which has been estimated to form $\frac{999}{1000}$ths of the whole cloud that hangs over an active volcano. In great eruptions it rises in prodigious quantities, and is rapidly condensed into a heavy rainfall. M. Fouqué calculated that during 100 days one of the parasitic cones on Etna had ejected vapour enough to form if condensed, 2,100,000 cubic mètres (462,000,000 gallons)

of water. But even from volcanoes which, like the Solfatara of Naples, have been dormant for centuries, steam sometimes still rises without intermission and in considerable volume. Jets of vapour

FIG. 32.—VIEW OF ETNA FROM THE TORRE ARCHIRAFI (SARTORIUS VON WALTERSHAUSEN).

rush out from clefts in the sides and bottom of a crater with a noise like that made by the steam blown off by a locomotive. The number of these funnels or fumaroles is often so large, and the amount of vapour so abundant, that only now and then, when the

wind blows the dense cloud aside, can a momentary glimpse be had of a part of the bottom of the crater; while at the same time the rush and roar of the escaping steam remind one of the din of some vast factory. Aqueous vapour rises likewise from rents on the outside of the volcanic cone. It issues so copiously from some flowing lavas that the stream of rock may be almost concealed from view by the cloud; and it continues to escape from fissures of the lava, far below the point of exit, for a long time after the rock has solidified and come to rest. So saturated, as it were, are many molten lavas with the vapour of water that Mr. Scrope even maintained that their mobility was due to this cause.[1]

Fig. 33.—View of Vesuvius as seen from Naples during the eruption of 1872, showing the dense clouds of condensed Aqueous Vapour.

Probably in no case is the steam mere pure vapour of water, though when it condenses into copious rain it is fresh and not salt water. It is associated with other vapours and gases disengaged from the potent chemical laboratory underneath. There seems to be always a definite order in the appearance of these vapours, though it may vary for different volcanoes. The hottest and most active fumaroles contain probably all the gases and vapours of a volcano, but, as the heat diminishes, the series of gaseous emanations is reduced. Thus in the Vesuvian eruption of 1855–56, the lava, as it cooled and hardened, gave out successively vapours of hydrochloric acid, chlorides, and sulphurous acid; then steam; and, finally, carbon dioxide and combustible gases.[2] More recent observations tend

[1] *Considerations on Volcanoes* (1825), p. 110.

[2] C. Sainte-Claire Deville and Leblanc, *Ann. Chim. et Phys.* 1858, lii. p. 19, *et seq.*

to corroborate the deductions of C. Sainte-Claire Deville that the nature of the vapours evolved depends on the temperature or degree of activity of the volcanic orifice, chlorine (and fluorine) emanations indicating the most energetic phase of eruptivity, sulphurous gases a diminishing condition, and carbonic acid (with hydrocarbons) the dying out of the activity. A "solfatara," or vent emitting only gaseous discharges, is believed to pass through these successive stages. Wolf observed that on Cotopaxi while hydrochloric acid, and even free chlorine escaped from the summit of the cone, sulphuretted hydrogen and sulphurous acid issued from the middle and lower slopes.[1] Fouqué's studies at Santorin have shown also that from submarine vents a similar order of appearance obtains among the volcanic vapours, hydrochloric and sulphurous acids being only found at points of emission having a temperature above 100° C., while carbon dioxide, sulphuretted hydrogen and nitrogen occur at all the fumaroles, even where the temperature is not higher than that of the atmosphere.[2]

The following are the chief gases evolved at volcanic fumaroles. Hydrochloric acid is abundant at Vesuvius, and probably at many other vents whence it has not been recorded. It is recognisable by its pungent, suffocating fumes, which make approach difficult to the clefts from which it issues. Sulphuretted hydrogen and sulphurous acid are distinguishable by their odours. The liability of the former gas to decomposition leads to the deposition of a yellow crust of sulphur, and perhaps also to the production of the sulphuric acid observed at active vents. Allusion has already been made (p. 53) to the emission of free hydrogen or of combustible compounds of this gas by Vesuvius. At the eruption of Santorin in 1866 these gases were also distinctly recognised by Fouqué, who for the first time established the existence of true volcanic flames. These were again studied spectroscopically in the following year by Janssen, who found them to arise essentially from the combustion of free hydrogen, but with traces of chlorine, soda, and copper. Fouqué determined by analysis that immediately over the focus of eruption free hydrogen formed thirty per cent. of the gases emitted, but that the proportion of this gas rapidly diminishes with distance from the active vents and hotter lavas, while at the same time the proportion of marsh gas and carbon dioxide rapidly increases. The gaseous emanations collected by him were found to contain abundant free oxygen as well as hydrogen. One analysis gave the following results: carbon dioxide 0·22, oxygen 21·11, nitrogen 21·90, hydrogen 56·70, marsh gas 0·07, = 100·00. This gaseous mixture, on coming in contact with a burning body, at once burns with a sharp explosion. Fouqué infers that the water-vapour of volcanic vents may exist in a state of dissociation within the molten magma whence lavas rise.[3] Carbon dioxide rises chiefly (*a*) after an

[1] *Neues Jahrb.* 1878, p. 164. [2] "Santorin et ses éruptions," Paris, 1879.
[3] Fouqué, *op. cit.* p. 225.

eruption has ceased and the volcano relapses into quiescence; or (*b*) after volcanic action has otherwise become extinct. Of the former phase instances are on record at Vesuvius where an eruption has been followed by the emission of this gas so copiously from the ground as to suffocate hundreds of hares, pheasants, and partridges. Of the second phase good examples are supplied by the ancient volcanic regions of the Eifel and Auvergne, where the gas still rises in prodigious quantities. Bischof estimated that the volume of carbonic acid evolved in the Brohl Thal amounts to 5,000,000 cubic feet, or 300 tons of gas in one day. Nitrogen, derived perhaps from the decomposition of atmospheric air dissolved in the water which penetrates into the volcanic foci, has been frequently detected among the gaseous emanations. At Santorin it was found to form from 4 to 88 per cent. of the gas obtained from different fumaroles.[1]

With these gases and vapours are associated many substances which, sublimed by the volcanic heat or resulting from reactions among the escaping vapours, appear as deposits along crevices and surfaces wherein they reach the air and are cooled. Besides sulphur, there are several chlorides (particularly that of sodium, and less abundantly those of iron, copper, and lead); also free sulphuric acid, sal-ammoniac, specular iron, oxide of copper, boracic acid, alum, sulphate of lime, and other substances. Sodium chloride sometimes appears so abundantly that wide spaces of a volcanic cone, as well as of the newly-erupted lava, are crusted with salt, which can even be profitably removed by the inhabitants of the district. Considerable quantities of these chlorides may thus be buried between successive sheets of lava, and in long subsequent times may give rise to mineral springs, as has been suggested with reference to the saline waters which issue from volcanic rocks of Old Red Sandstone and Carboniferous age in Scotland.[2] The iron-chloride forms a bright yellow and reddish crust on the crater walls, as well as on loose stones on the slopes of the cone. Specular iron from the decomposition of iron-chloride forms abundantly as thin lamellæ in the fissures of Vesuvian lavas. In the spring of 1873 the author observed delicate brown filaments of tenorite (copper-oxide, CuO) forming in clefts of the crater of Vesuvius. They were upheld by the upstreaming current of vapour until blown off by the wind. Fouqué has described tubular vents in the lavas of Santorin wherein crystals of anorthite, sphene and pyroxene have recently been formed by sublimation.

2. **Water.**—In connection with the aqueous vapour of volcanoes, reference may be made here to the abundant discharges of water which accompany some volcanic explosions. Three sources of this water may be assigned:—(1) from the melting of snow by a rapid accession of temperature previous to or during an eruption; this takes place from time to time on Etna, in Iceland, and among the snowy ranges of the Andes, where the cone of Cotopaxi is said to have been entirely

[1] Fouqué, *loc. cit.* [2] Geikie, *Proc. Roy. Soc. Edin.* ix. p. 367.

divested of its snow in a single night by the heating of the mountain; (2) from the condensation of the vast clouds of steam which are discharged during an eruption; this undoubtedly is the chief source of the destructive torrents so frequently observed to form part of the phenomena of a great volcanic explosion; and (3) from the disruption of reservoirs of water filling subterranean cavities, or of lakes occupying crater-basins; this has several times been observed among the South American volcanoes, where immense quantities of dead fish, which inhabited the water, have been swept down with the escaping torrents. The volcano of Agua, in Guatemala, has never been known to discharge anything but water. In the beginning of the year 1817 an eruption took place at the large crater of Idjèn, one of the volcanoes of Java, whereby a hot steaming lake of acid water was discharged with frightful destruction down the slopes of the mountain. After the explosion the basin filled again with water, but its temperature was no longer high.

In many cases the water rapidly collects volcanic dust as it rushes down, and soon becomes a pasty mud; or it issues at first in this condition from the volcanic reservoirs after violent detonations. Hence arise what are termed m u d - l a v a s, or aqueous lavas, which in many respects behave like true lavas. This volcanic mud eventually consolidates into one of the numerous forms of tuff, a rock which, as has been already stated (p. 161), varies greatly in the amount of its coherence, in its composition, and in its internal arrangement. Obviously, unless where subsequently altered, it can possess none of the crystalline structure of true lava. As a rule it betrays its aqueous origin by more or less distinct evidence of stratification, by the multifarious pebbles, stones, blocks of rock, tree-trunks, branches, shells, bones, skeletons, &c., which it has swept along in its course and preserved within its mass. Sections of this compacted tuff may be seen at Herculaneum. The *trass* of the Brohl Thal and other valleys in the Eifel district, referred to on p. 164, is another example of an ancient volcanic mud.

3. **Lava.**—The term lava is applied generally to all the molten rocks of volcanoes.[1] The use of the word in this broad sense is of great convenience in geological descriptions, by directing attention to the leading character of the rocks as molten products of volcanic action, and obviating the confusion and errors which are apt to arise from an ill-defined or incorrect lithological terminology. Precise definitions of the rocks, such as those above given in Book II., can be added when required. A few remarks regarding some of the general lithological characters of lavas may be of service here; the behaviour of the rocks in their emission from volcanic orifices will be described in § 2.

While still flowing or not yet cooled, lavas differ from each other in the extent to which they are impregnated with gases and

[1] "Alles ist Lava was im Vulkane fliesst und durch seine Flüssigkeit neue Lagerstätter einnimmt" is Leopold von Buch's comprehensive definition.

vapours. Some appear to be saturated, others contain a much smaller gaseous impregnation; and hence arise important distinctions in their behaviour (pp. 218, 224). After solidification lavas present some noticeable characters then easily ascertainable. (1) Their average specific gravity may be taken as ranging between 2·37 and 3·22. (2) The heavier varieties contain much magnetic or titaniferous iron, with augite and olivine, their composition being basic, and their proportion of silica averaging about 45 or 50 per cent. In this group come the basalts, dolerites, nepheline-lavas, and leucite-lavas. The lighter varieties contain commonly a minor proportion of metallic bases, but are rich in silica, their percentage of that acid ranging between 60 and 80. They are thus not basic but acid rocks. Among their more important species trachyte, rhyolite, obsidian, pitchstone, and pumice may be enumerated. Some intermediate varieties (augite-andesite, hornblende-andesite) connect the acid and basic series. (3) They differ much in structure and texture. (*a*) Some are entirely crystalline, consisting of nothing but an interlaced mass of crystals and crystalline particles, as in some dolerites, and granitoid liparites. Even quartz, which used to be considered a non-volcanic mineral characteristic of the older and chiefly of the plutonic eruptive rocks, has been observed in large crystals in modern lava as in liparite and quartz-andesite.[1] (*b*) Some show more or less of a half-glassy or stony matrix, in which the constituent crystals are imbedded; this is the most common arrangement. (*c*) Others are entirely vitreous, such crystals or crystalline particles as occur in them being quite subordinate, and, so to speak, accidental enclosures in the main glassy mass. Obsidian or volcanic glass is the type of this group. (*d*) They further differ in the extent to which minute pores or larger cellular spaces have been developed in them. According to Bischof the porosity of lavas depends on their degree of liquidity, a porous lava or slag, when reduced in his experiments to a thin-flowing consistency, hardening into a mass as compact as the densest lava or basalt.[2] But the presence of interstitial steam in lavas, by expanding the still molten stone, produces an open cellular texture, somewhat like that of ill-baked bread. Such a vesicular arrangement very commonly appears on the upper surface of a lava current, which assumes a slaggy or cindery aspect. (4) They vary greatly in colour and general external aspect. The heavy basic lavas are usually dark grey, or almost black, though, on exposure to the weather, they acquire a brown tint from the oxidation and hydration of their iron. Their surface is commonly rough and ragged, until it has been sufficiently decomposed by the atmosphere to crumble into excellent soil which, under favourable circumstances, supports a luxuriant vegetation. The less dense lavas, such as phonolites and trachytes, are frequently paler in colour, sometimes pale yellow or buff, and decompose into

[1] Wolf, *Neues Jahrb.* 1874, p. 377.
[2] *Chem. und Phys. Geol.* Supp. (1871), p. 144.

light soils; but the obsidians present rugged black sheets of rock roughened with ridges and heaps of grey froth-like pumice. Some of the most brilliant surfaces of colour in any rock scenery on the globe are to be found among volcanic rocks. The walls of active craters glow with endless hues of red and yellow. The Grand Cañon of the Yellowstone River has been dug out of the most marvellously tinted lavas and tuffs.

4. **Fragmentary Materials.**—Under this title we include all the substances which, driven up into the air by volcanic explosions, fall in solid form to the ground—the dust, ashes, sand, cinders, and blocks of every kind which are projected from a volcanic orifice. These materials differ in composition, texture, and appearance, even during a single eruption, and still more in successive explosions of the same volcano. For the sake of convenience separate names are applied to some of the more distinct varieties, of which the following may be enumerated.

(1) Ashes and Sand.—In many eruptions vast quantities of an exceedingly fine light grey powder are ejected. As this substance greatly resembles what is left after a piece of wood or coal is burnt in an open fire, it has been popularly termed *ash*, and this name has been adopted by geologists. If, however, by the word ash the result of combustion is implied, its employment to denote any product of volcanic action must be regretted as apt to convey a wrong impression. The fine ash-like dust ejected by a volcano is merely lava in an extremely fine state of comminution. So minute are the particles that they find their way readily through the finest chinks of a closed room, and settle down upon floor and furniture as ordinary dust does when a house is shut up. From this finest form of material gradations may be traced, through what is termed volcanic sand, into the coarser varieties of ejected matter. In composition the ash and sand vary necessarily with the nature of the lava from which they are derived. Their microscopic structure, and especially their abundant microliths, crystals, and volcanic glass have been already referred to (p. 162).

(2) Lapilli or rapilli are ejected fragments ranging from the size of a pea to that of a walnut, round, subangular, or angular in shape, and having the same indefinite range of composition as the finer dust. As a rule, the coarse fragments fall nearest the focus of eruption. Sometimes they are solid fragments of lava, but more usually they have a cellular texture, while sometimes they are so light and porous as to float readily on water, and when ejected near the sea, to cover its surface. Well-formed crystals occur in the lapilli of many volcanoes, and are also ejected separately. It has been observed indeed that the fragmentary materials not infrequently contain finer crystals than the accompanying lava.[1]

(3) Volcanic Blocks are larger pieces of stone, often angular in shape. In some cases they appear to be fragments loosened from already solidified rocks in the chimney of the volcano. Hence we

[1] S. von Waltershausen, *Island und Sicilien*, 1853, p. 328.

find among them pieces of non-volcanic rocks as well as of older tuffs and lavas recognisably belonging to early eruptions. In many cases they are ejected in enormous quantities during the earlier phases of violent eruption. The great explosion from the side of Ararat in 1840 was accompanied by the discharge of a vast quantity of fragments over a space of many square miles around the mountain. Whitney has described the occurrence in California of beds of such fragmentary volcanic breccia hundreds of feet thick and covering many square miles of surface. Junghuhn in his account of the eruption in Java in 1772, mentions that a valley ten miles long was filled to an average depth of fifty feet with angular volcanic debris.[1]

Among the earlier eruptions of a volcano fragments of the rocks through which the vent has been drilled may frequently be observed. These are in many cases not volcanic. Blocks of schist and granitoid rocks occur in the cinder-beds at the base of the volcanic series of Santorin. In the older tuffs of Somma pieces of altered limestone are abundant and often contain cavities lined with the characteristic "Vesuvian minerals." Blocks of a coarsely crystalline granitoid lava have been particularly observed both on Etna and Vesuvius. In the year 1870 a mass of that kind, weighing several tons, was to be seen lying at the foot of Vesuvius, within the entrance to the Atrio del Cavallo. Similar blocks occur among the Carboniferous volcanic pipes of central Scotland, together sometimes with fragments of sandstone, shale, or limestone, not infrequently full of Carboniferous fossils.[2]

(4) Volcanic Bombs and Slags.—These have originally formed portions of the column of lava ascending the pipe of the volcano, and have been detached and hurled into the air by the successive explosions of steam. A bomb (Fig. 34) is a round, elliptical, or pear-shaped, often discoidal mass of lava, from a few inches to several feet in diameter; sometimes tolerably solid throughout, more usually coarsely cellular inside. Not infrequently its interior is hollow, and the bomb then consists of a shell which is most close-grained towards the outside. There can be no doubt that, when torn by eructations of steam from the surface of the boiling lava, the material of these bombs is in as thoroughly molten a condition as the rest of the mass. From the rotatory motion imparted by its ejection it takes a circular form, and in proportion to its rapidity of rotation and fluidity is the amount of its "flattening at the poles." The centrifugal force within allows the expansion of the interstitial vapour, while the outer surface rapidly cools and solidifies; hence the solid crust, and the porous or cavernous interior. Such bombs, varying from the size of an apple to that of a man's body, were found by Darwin abundantly strewn over the ground in the Island of Ascension;

[1] But see the remarks already made on volcanic conglomerates, *ante*, p. 163.
[2] *Trans. Roy. Soc. Edin.* xxxix. p. 459. See *postea*, Book IV. section vii. § 1, 4.

they were also ejected in vast quantities during the eruption of Santorin in 1866.[1] Among the tuffs of the Eifel region small bombs, consisting mostly of granular olivine, are of common occurrence, as also pieces of sanidine or other less fusible minerals

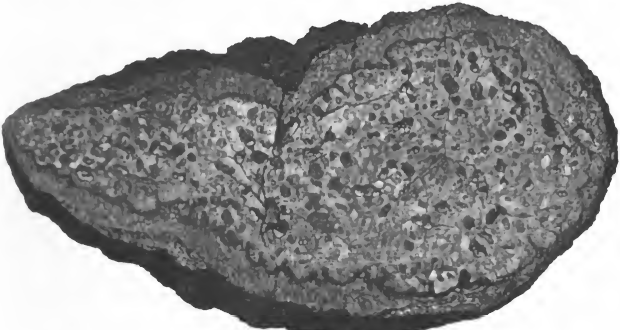

FIG. 34.—SECTION OF VOLCANIC BOMB, ONE-THIRD NATURAL SIZE.

which have segregated out of the magma before ejection. When the ejected fragment of lava has a rough irregular form, and a porous structure like the clinker of an iron-furnace, it is known as a slag.[2]

The fragmentary materials erupted by a volcano and deposited around it acquire by degrees more or less consolidation, partly from the mere pressure of the higher upon the lower strata, partly from the influence of infiltrating water. It has been already stated (p. 161) that different names are applied to the rocks thus formed. The coarse, tumultuous, unstratified accumulation of volcanic debris within a crater or funnel is called Agglomerate. When the debris, though still coarse is more rounded, and is arranged in a stratified form on the slopes of the cone or on the plain beyond, it becomes a Volcanic Conglomerate. The finer-grained varieties, formed of dust and lapilli, are included in the general designation of Tuffs. These are usually pale-yellowish, greyish, or brownish, sometimes black rocks, granular, porous, and often incoherent in texture.

Organic remains sometimes occur in tuff. Where volcanic debris has accumulated over the floor of a lake, or of the sea, the entombing and preserving of shells and other organic objects must continually take place. Examples of this kind are cited in later pages of this volume from older geological formations. Professor Guiscardi of

[1] *Geological Observations on Volcanic Islands*, 2nd edit. p. 42. Fouqué, *op. cit.* p. 79.

[2] On the ratio between the pores and volume of the rock in slags and lavas, see determinations by Bischof, *Chem. und Phys. Geol.* Supp. (1871), p. 158.

Naples has found about 100 species of marine shells of living species in the old tuffs of Vesuvius. Marine shells have been picked up within the crater of Monte Nuovo, and have been frequently observed in the old or marine tuff of that district. Showers of ash, or sheets of volcanic mud often preserve land-shells, insects, and vegetation living on the area at the time. The older tuffs of Vesuvius have yielded many remains of the shrubs and trees which at successive periods have clothed the flanks of the mountain. Fragments of coniferous wood which once grew on the tuff-cones of Carboniferous age in central Scotland are abundant in the "necks" of that region.[1]

§ 2. Volcanic Action.

Volcanic action may be either constant or periodic. Stromboli, in the Mediterranean, so far as we know, has been uninterruptedly emitting hot stones and steam, from a basin of molten lava, since the earliest period of history. Among the Moluccas the volcano Sioa, and in the Friendly Islands that of Tofua, have never ceased to be in eruption since their first discovery. The lofty cone of Sangay, among the Andes of Quito, is always giving off hot vapours; Cotopaxi, too, is ever constantly active. But, though examples of unceasing action may thus be cited from widely different quarters of the globe, they are nevertheless exceptional. The general rule is that a volcano breaks out from time to time with varying vigour, and after longer or shorter intervals of quiescence.

Active, Dormant, and Extinct Phases.—It is usual to class volcanoes as *active*, *dormant*, and *extinct*. This arrangement, however, often presents considerable difficulty in its application. An active volcano cannot of course be mistaken, for even when not in eruption it shows by its discharge of steam and hot vapours that it might break out into activity at any moment. But in many cases it is impossible to decide whether a volcano should be called extinct or only dormant. The volcanoes of Silurian age in Wales, of Carboniferous age in Ireland, of Permian age in the Harz, of Miocene age in the Hebrides, of younger Tertiary age in the western States and Territories of North America, are certainly all extinct. But the Miocene volcanoes of Iceland are still represented there by Skaptar-Jökull, Hecla, and their neighbours. Somma, in the first century of the Christian era, would have been naturally regarded as an extinct volcano. Its fires had never been known to have been kindled; its vast crater was a wilderness of wild vines and brushwood, haunted, no doubt by wolf and wild boar. Yet in a few days, in the autumn of the year 79, the half of the crater walls was blown out by a terrific series of explosions, the present Vesuvius was then formed within the limits of the earlier crater, and since that time volcanic action has been intermittently exhibited up to the present day. Some of the intervals of quietude, however, have been

[1] *Trans. Roy. Soc. Edin.* xxix. p. 470; *postea*, Book IV. section vii. § i. 4.

so considerable that the mountain might then again have been claimed as an extinct volcano. Thus, in the 131 years between 1500 and 1631, so completely had eruptions ceased that the crater had once more become choked with copsewood. A few pools and springs of very salt and hot water remained as memorials of the former condition of the mountain. But this period of quiescence closed with the eruption of 1631,—the most powerful of all the known explosions of Vesuvius, except the great one of 79. In the island of Ischia, Mont' Epomeo was last in eruption in the year 1302, its previous outburst having taken place, it is believed, about 17 centuries before that date. From the craters of the Eifel, Auvergne, the Vivarais, and central Italy, though many of them look as if they had only recently been formed, no eruption has been known to come during the times of human history or tradition. In the west of North America, from Arizona to Oregon, numerous stupendous volcanic cones occur, but even from the most perfect and fresh of them nothing but steam and hot vapours have yet been known to proceed. But the existence there of hot springs and geysers testifies to the continued existence of one phase of volcanic action.

In short, no real distinction can be drawn between dormant and extinct volcanoes. Volcanic action is apt to show itself again and again, even at vast intervals within the same regions and over the same sites. The dormant or waning condition of a volcano, when only steam and various gases and sublimates are given off, is sometimes called the Solfatara phase, from the well-known dormant crater of that name near Naples.

Sites of Volcanic Action.—Volcanoes may break through any geological formation. In Auvergne, in the Miocene period, they burst through the granitic and gneissose plateau of central France. In Lower Old Red Sandstone times they pierced contorted Silurian rocks in central Scotland. In late Tertiary and post-Tertiary ages they found their way through recent soft marine strata, and formed the huge piles of Etna Somma and Vesuvius; while in North America, during the same cycle of geological time, they flooded with lava and tuff many of the river courses, valleys, and lakes of Nevada, Utah, Wyoming, Idaho and adjacent territories. On the banks of the Rhine, at Bonn and elsewhere, they have penetrated some of the older alluvia of that river. In many instances, also, newer volcanoes have appeared on the sites of older ones. In Scotland the Carboniferous volcanoes have risen on the ruins of those of the Old Red Sandstone, those of the Permian period have broken out among the earlier Carboniferous eruptions, while the Miocene lavas have been injected into all these older volcanic masses. The newer *puys* of Auvergne were sometimes erupted through much older and already greatly denuded basalt-streams. Somma and Vesuvius have risen out of the great Neapolitan plain of older marine tuff, while in central Italy newer cones have been thrown up upon the great Roman plain of more ancient volcanic debris. The vast Snake River lava-fields of

Idaho overlie denuded masses of earlier trachytic lavas, and similar proofs of a long succession of intermittent and widely-separated volcanic outbursts can be traced northwards into the Yellowstone Valley.

When a volcanic vent is opened it might be supposed always to find its way to the surface along some line of fissure, valley or deep depression. No doubt many, if not most, modern as well as ancient vents, especially those of large size, have done so. It is a curious fact, however, that in innumerable instances minor vents have appeared where there was no line of dislocation to aid them. This has been well shown by a study of the ancient volcanic rocks of the Old Red Sandstone, Carboniferous and Permian formations of Scotland.[1] It has likewise been most impressively demonstrated by the way in which the minor basalt cones and craters of Utah have broken out near the edges or even from the face of cliffs rather than at the bottom. Captain Dutton remarks that among the high plateaux of Utah, where there are hundreds of basaltic craters, the least common place for them is at the base of a cliff, and that, though they occur near faults, it is almost always on the lifted, rarely upon the depressed side.[2] On a small scale a similar avoidance of the valley bottom is shown on the Rhine and Moselle, where eruptions have taken place close to the edge of the plateau through which these rivers wind. Why outbreaks should have occurred in this way is a question not easily answered. It suggests that the existing depressions and heights of the earth's surface may sometimes be insignificant features, compared with the depth of the sources of volcanoes and the force employed in volcanic eruption.

Conditions of Eruption.—Leaving for the present the general question of the cause of volcanic action, it may be here remarked that the conditions determining any particular eruption are still unknown. An attempt has been made to show that the explosions of a volcano are to some extent regulated by the conditions of atmospheric pressure over the area at the time. In the case of a volcanic funnel like Stromboli, where, as Scrope pointed out, the expansive subterranean force within, and the repressive effect of atmospheric pressure without, just balance each other, any serious disturbance of that pressure might be expected to make itself evident by a change in the condition of the volcano. Accordingly, it has long been remarked by the fishermen of the Lipari Islands that in stormy weather there is at Stromboli a more copious discharge of steam and stones than in fine weather. They make use of the cone as a weather-glass, the increase of its activity indicating a falling, and the diminution a rising barometer. In like manner, Etna, according to S. von Waltershausen is most active in the winter months. When we remember the connexion now indubitably established between a more copious discharge of fire-damp in mines and a lowering of atmospheric pressure, we may be prepared to find a similar influence affecting the

[1] *Trans. Roy. Soc. Edin.* xxix. p. 437.

[2] "High Plateaux of Utah," *Geol. and Geog. Survey of Territories*, 1880, p. 62.

escape of vapours from the upper surface of the lava column of a volcano; for it is not so much to the lava itself as to the expansive vapours impregnating it that the manifestations of volcanic activity are due. Among the Vesuvian eruptions since the middle of the 17th century, the number which took place in winter and spring was to that of those which broke out in summer and autumn as 7 to 4. But there may be other causes besides atmospheric pressure concerned in these differences; the preponderance of rain during the winter and spring may be one of these. According to Mr. Coan, previous to the great Hawaian eruption of 1868 there had been unusually wet weather, and to this fact he attributes the exceptional severity of the earthquakes and volcanic explosions. But at most the effects of varying atmospheric pressure can only slightly modify volcanic activity. Eruptions like the great one of Cotopaxi in 1877 have in innumerable instances taken place without, so far as can be ascertained, any reference to atmospheric conditions.

Kluge has sought to trace a connexion between the years of maximum and minimum sun-spots and those of greatest and feeblest volcanic activity, and has constructed lists to show that years which have been specially characterized by terrestrial eruptions have coincided with those marked by few sun-spots and diminished magnetic disturbance.[1] Such a connexion cannot be regarded as having yet been satisfactorily established. Again, the same author has called attention to the frequency and vigour of volcanic explosions at or near the time of the August meteoric shower. But in this case, likewise, the cited examples can hardly yet be looked upon as more than coincidences.

Occasional Periodicity of Eruptions.—The case of Kilauea, in Hawaii, seems to show a regular system of eruptive periods. Dana has pointed out that outbreaks of lava have taken place from that volcano at intervals of from eight to nine years, this being the time required to fill the crater up to the point of outbreak, or to a depth of 400 or 500 feet. But the great eruption of 1868 did not occur until after an interval of 18 years. The same author suggests that the missing eruption may have been submarine.[2]

General sequence of Events in an Eruption.—The approach of an eruption is not always indicated by any premonitory symptoms, for many tremendous explosions are recorded to have taken place in different parts of the world without perceptible warning. Much in this respect would appear to depend upon the condition of liquidity of the lava, and the amount of resistance offered by it to the passage of the escaping vapours through its mass. In Hawaii, where the lavas are remarkably liquid, vast out-pourings of them have taken place quietly without earthquakes during the present century. But even there the great eruption of 1868 was accompanied by tremendous earthquakes.

[1] *Ueber Synchronismus und Antagonismus*, p. 72.
[2] On the periodicity of eruptions, see Kluge, *Neues Jahrb.* 1862, p. 582.

The eruptions of Vesuvius are often preceded by failure or diminution of wells and springs. But more frequent indications of an approaching outburst are conveyed by sympathetic movements of the ground. Subterranean rumblings and groanings are heard; slight tremors succeed, increasing in frequency and violence till they become distinct earthquake shocks. The vapours from the crater grow more abundant as the lava column in the pipe or funnel of the volcano ascends, forced upward and kept in perpetual agitation by the passage of elastic vapours through its mass. After a long previous interval of quiescence, there may be much solidified lava towards the top of the funnel which will restrain the ascent of the still molten portion underneath. A vast pressure is thus exercised on the sides of the cone which, if too weak to resist, will open in one or more rents, and the liquid lava will issue from the outer slope of the mountain; or the energies of the volcano will be directed towards clearing the obstruction in the chief throat, until, with tremendous explosions, and the rise of a vast cloud of dust and fragments, the bottom and sides of the crater are finally blown out, and the top of the cone disappears. The lava may now escape from the lowest part of the lip of the crater, while, at the same time, immense numbers of red-hot bombs, scoriæ, and stones are shot up into the air. The lava at first rushes down like one or more rivers of melted iron, but, as it cools, its rate of motion lessens. Clouds of steam rise from its surface, as well as from the central crater. Indeed, every successive paroxysmal convulsion of the mountain is marked, even at a distance, by the rise of huge ball-like wreaths or clouds of steam, mixed with dust and stones, forming a column which towers sometimes a couple of miles above the summit of the cone. By degrees these eructations diminish in frequency and intensity. The lava ceases to issue, the showers of stones and dust decrease, and after a time, which may vary from hours to days or months, even in the *régime* of the same mountain, the volcano becomes once more tranquil.[1]

In the investigation of the subject, the student will naturally devote attention specially to those aspects of volcanic action which have more particular geological interest from the permanent changes with which they are connected, or from the way in which they enable us to detect and realize conditions of volcanic energy in former periods.

Fissures.—The convulsions which culminate in the formation of a volcano usually split open the terrestrial crust with a more or less nearly rectilinear fissure. In the subsequent progress of the mountain, the ground at and around the focus of action is liable to be again and again rent open by other fissures. These tend to diverge from the focus; but around the vent where the rocks have been most exposed to concussion the fissures sometimes intersect each other in all directions. In the great eruption of Etna, in the year 1669, a

[1] A remarkably good account of the great eruption of Cotopaxi in June, 1877, by Dr. Th. Wolf will be found in *Neues Jahrb.* 1878, p. 113.

series of six parallel fissures opened on the side of the mountain. One of these, with a breadth of two yards, ran for a distance of 12 miles, in a somewhat winding course, to within a mile of the top of the cone. Similar fissures, but on a smaller scale, have often been observed on Vesuvius; and they are recorded from many other volcanoes.

Two obvious causes may be assigned for the fissuring of a volcanic cone:—(1) the enormous expansive force of the imprisoned vapours acting upon the walls of the funnel and convulsing the cone by successive explosions; and (2) the hydrostatic pressure of the lava-column in the funnel, which may be taken to be about 120 lb. per square inch, or nearly 8 tons on the square foot, for each 100 feet of depth. Both of these causes may act simultaneously.

Into the rents thus formed the molten lava naturally finds its way, or is forced, and it solidifies there like iron in a mould. The cliffs of many an old crater show how marvellously they have been injected by such *veins* or *dykes* of lava. Those of Somma, and the Val del Bove on Etna (Fig. 35), which have long been known, project now from the

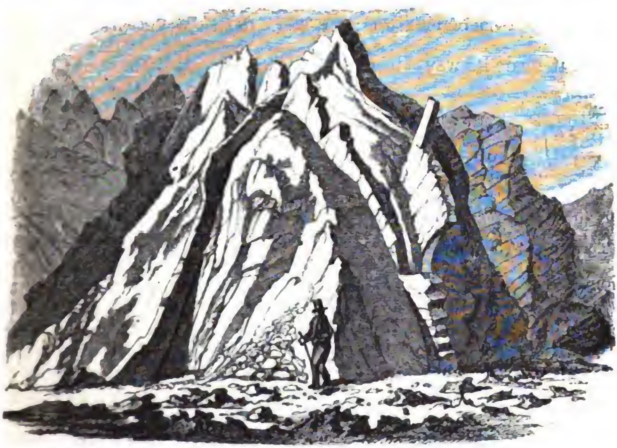

FIG. 35.—VIEW OF LAVA-DYKES, VAL DEL BOVE, ETNA (ABICH).

softer tuffs like walls of masonry. The crater cliffs of Santorin also present an abundant series of dykes. Such wedges of solid rock driven into the cone must widen its dimensions, for the fissures are not due to shrinkage, although doubtless the loosely piled fragmentary materials in the course of their consolidation develop lines of joint. Sometimes the lava has evidently risen in a state of extreme fluidity and has at once filled the rents prepared for it, cooling rapidly on the outside as a true volcanic glass, but assuming a dis-

tinctly crystalline structure inside (*ante*, p. 105). Dykes of this kind with a vitreous crust on their sides may be seen on the crater-wall of Somma and not uncommonly among basalt dykes in Iceland and Scotland. In other cases the lava had probably already acquired a lithoid character while still rising in the fissure, and in this condition was able to push aside and even contort the strata of tuff through

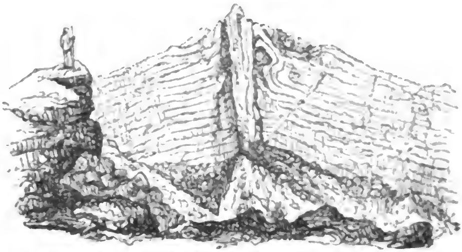

Fig. 36.—Dyke contorting beds of Tuff. Crater of Vesuvius (Abich).

which it made its way (Fig. 36). There can be little doubt that in the architecture of a volcano dykes must act the part of huge beams and girders (Fig. 37), binding the loose tuffs and intercalated lavas together and strengthening the cone against the effects of subsequent convulsions.

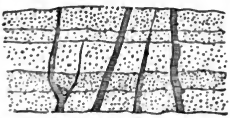

Fig. 37.—Section of Dykes of Lava traversing the bedded Tuffs of a Volcanic Cone.

From this point of view an explanation suggests itself of the observed alternations in the character of a volcano's eruptions. These alternations may depend in great measure upon the relation between the height of the cone on the one hand and the strength of its sides on the other. When the sides have been well braced together by interlacing dykes, and further thickened by the spread of volcanic materials all over their slopes, they may resist the effects of explosion and of the pressure of the ascending lava column. In this case the volcano may find relief only from its summit, and if the lava flows forth, it will do so from the top of the cone. As the cone increases in elevation, however, the pressure from within upon its sides augments. Eventually egress is once more established on the flanks by means of fissures, and a new series of lava-streams is poured out over the lower slopes.

Though lava very commonly issues from the lateral fissures on a volcanic cone, it may sometimes approach the surface in them without actually flowing out. The great fissure on Etna in 1669, for example, was visible even from a distance by the long line of vivid light which rose from the incandescent lava within. Again, it frequently happens that minor volcanic cones are thrown up on the

line of a fissure, either from the congelation of the lava round the point of emission, or from the accumulation of ejected scoriæ round the fissure-vent.

Explosions.—Apart from the appearance of visible fissures, volcanic energy may be, as it were, concentrated on a given point, which will usually be the weakest in the structure of that part of the terrestrial crust, and from which the solid rock, shattered into pieces, is hurled into the air, followed by the ascent of volcanic materials. This operation has often been observed in volcanoes already formed, and has even been witnessed on ground previously unoccupied by a volcanic vent. The history of the cone of Vesuvius brings before us a long series of such explosions, beginning with that of 79—and coming down to the present day. Even now, in spite of all the lava and ashes poured out during the last eighteen centuries, it is easy to see how stupendous must have been that earliest explosion, by which the southern half of the ancient crater was blown out. At every successive important eruption, a similar but minor operation takes place within the present cone. The hardened cake of lava forming

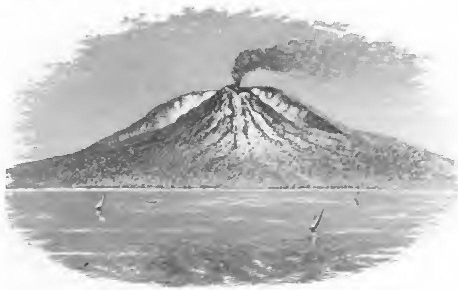

FIG. 38.—VIEW OF VESUVIUS FROM THE SOUTH,
Showing the remaining part of the old crater-wall of Somma behind.

the floor is burst open, and with it there usually disappears much of the upper part of the cone, and sometimes, as in 1872, a large segment of the crater-wall. The islands of Santorin (Figs. 58 and 59) bring before us evidence of a prehistoric catastrophe of a similar nature, by which a large volcanic cone was blown up. The existing outer islands are a chain of fragments of the periphery of the cone, the centre of which is now occupied by the sea. In the year 1538 a new volcano, Monte Nuovo, was formed in 24 hours on the margin of the Bay of Naples. An opening was drilled by successive explosions, and such quantities of stones, scoriæ, and ashes were thrown out from it as to form a hill that rose 440 English feet above the sea-level, and was more than a mile and a half in circumference. Most of the fragments now to be seen on the slopes of this cone and inside its beautifully

perfect crater are of various volcanic rocks, many of them being black scoriæ; but pieces of Roman pottery, together with fragments of the older underlying tuff, and some marine shells, have been obtained—doubtless part of the soil and subsoil dislocated and ejected during the explosions.

It is not necessary, and it does not always happen, that any actual solid or liquid volcanic rock is erupted by explosions that shatter the rocks through which the funnel passes. Thus among the cones of the extinct volcanic tract of the Eifel, some occur consisting entirely, or nearly so, of comminuted debris of the surrounding Devonian greywacke and slate through which the various volcanic vents have been opened (see pp. 206, 243). Evidently in such cases only elastic vapours forced their way to the surface; and we see what probably often takes place in the early stages of a volcano's history, though the fragments of the underlying disrupted rocks are in most instances buried and lost under the far more abundant subsequent volcanic materials. Sections of small ancient volcanic necks or pipes sometimes afford an excellent opportunity of observing that these orifices were originally opened by the blowing out of the solid crust and not by the formation of fissures. Examples will be cited in later pages from Scottish volcanic rocks of Old Red Sandstone, Carboniferous, and Permian age. The orifices are there filled with fragmentary materials wherein portions of the surrounding and underlying rocks form a noticeable proportion.[1]

Showers of Dust and Stones.—A communication having been opened, either by fissuring or explosion, between the heated interior and the surface, fragmentary materials are commonly ejected from it, consisting at first mainly of the rocks through which the orifice has been opened, afterwards of volcanic substances. In a great eruption vast numbers of red-hot stones are shot up into the air, and fall back partly into the crater and partly on the outer slopes of the cone. According to Sir W. Hamilton, cinders were thrown by Vesuvius, during the eruption of 1779, to a height of 10,000 feet. Instances are known where large stones, ejected obliquely, have described huge parabolic curves in the air, and fallen at a great distance. Stones 8 lb. in weight occur among the ashes which buried Pompeii. The volcano of Antuco in Chili is said to send stones flying to a distance of 36 (?) miles, and Cotopaxi is reported to have hurled a 200-ton block 9 miles.[2]

But in many great eruptions, besides a constant shower of stones and scoriæ, a vast column of exceedingly fine dust rises out of the crater, sometimes to a height of more than a mile, and then spreads outwards like a sheet of cloud. So dense sometimes is this dust-cloud that the sun may be obscured, and for days together the darkness of night may reign for miles around the volcano. In 1822, at Vesuvius, the ashes not only fell thickly on the villages round the base of the

[1] *Trans. Roy. Soc. Edin.* xxix. p. 458.
[2] D. Forbes, *Geol. Mag.* vii. p. 220.

mountain, but travelled as far as Ascoli, which is 56 Italian miles distant from the volcano on one side, and as Casano, 105 miles on the other. The eruption of Cotopaxi, on June 26th, 1877, began by an explosion that sent up a column of fine ashes to a prodigious height into the air, where it rapidly spread out and formed so dense a canopy as to throw the region below it into total darkness. So quickly did it diffuse itself, that in an hour and a half a previously bright morning became at Quito, 33 miles distant, a dim twilight, which in the afternoon passed into such darkness that the hand placed before the eye could not be seen. At Guayaquil, on the coast, 150 miles distant, the shower of ashes continued till the 1st of July. Dr. Wolf collected the ashes daily, and estimated that at that place there fell 315 kilogrammes on every square kilometre during the first thirty hours, and on the 30th of June, 209 kilogrammes in 12 hours.[1] Probably the most stupendous outpouring of volcanic ashes on record was that which took place, after a quiescence of 26 years, from the volcano Coseguina, in Nicaragua, during the early part of the year 1835. On that occasion utter darkness prevailed over a circle of 35 miles radius, the ashes falling so thickly that, even 8 leagues from the mountain, they covered the ground to a depth of about 10 feet. It was estimated that the rain of dust and sand fell over an area at least 270 geographical miles in diameter. Some of the finer materials, thrown so high as to come within the influence of an upper air-current, were borne away eastward, and fell, four days afterwards, at Kingston, in Jamaica—a distance of 700 miles. During the great eruption of Sumbawa, in 1815, the dust and stones fell over an area of nearly one million of square miles, and were estimated by Zollinger to amount to fully fifty cubic miles of material, and by Junghuhn to be equal to one hundred and eighty-five mountains like Vesuvius.

An inquiry into the origin of these showers of fragmentary materials brings vividly before us some of the essential features of volcanic action. We find that bombs, slags, and lapilli may be thrown up in comparatively tranquil states of a volcano, but that the showers of fine dust are discharged with violence, and only appear when the volcano becomes more energetic. Thus, at the constantly, but quietly, active volcano of Stromboli, the column of lava in the pipe may be watched rising and falling with a slow rhythmical movement. At every rise the surface of the lava swells up into blisters several feet in diameter, which by-and-by burst with a sharp explosion that makes the walls of the crater vibrate. A cloud of steam rushes out, carrying with it hundreds of fragments of the glowing lava, sometimes to a height of 1200 feet. It is by the ascent of steam through its mass that a column of lava is kept boiling at the bottom of the crater, and by the explosion of successive larger bubbles of steam that the various bombs, slags, and fragments of lava are torn off and tossed into the air. It has often been noticed at Vesuvius that each great concussion is accompanied by a huge ball-like cloud of steam which

[1] *Neues Jahrb.* 1878, p. 141.

rushes up from the crater. Doubtless it is the sudden escape of that steam which causes the explosion.

The varying degree of liquidity or viscosity of the lava probably modifies the force of explosions, owing to the different degrees of resistance offered to the upward passage of the absorbed gases and vapours. Thus explosions and accompanying scoriæ are abundant at Vesuvius, where the lavas are comparatively viscid; they are almost unknown at Kilauea, where the lava is remarkably liquid.

In tranquil conditions of a volcano the steam, whether collecting into larger or smaller vesicles, works its way upward through the substance of the molten lava, and as the elasticity of this compressed vapour overcomes the pressure of the overlying lava, it escapes at the surface, and there the lava is thus kept in ebullition. But this comparatively quiet operation, which may be watched within the craters of many active volcanoes, does not produce clouds of fine dust. The collision or friction of millions of stones ascending and descending in the dark column above the crater, though it must doubtless cause much dust and sand, can give rise to but an insignificant proportion of what is actually reduced to the condition of extreme subdivision necessary to produce widespread darkness and a thick far-reaching deposit of ashes. The explanation now accepted calls in the explosive action of steam as the immediate cause of the trituration. The aqueous vapour by which many lavas are so largely impregnated must exist interstitially far down in the lava-column, under an enormous pressure, and at a white heat. The sudden ascent of lava so constituted will relieve the pressure rapidly without sensibly affecting the temperature of the mass. Consequently the white-hot steam will at length explode, and reduce the molten mass containing it to the finest powder, like water shot out of a gun.

Evidently no part of the operations of a volcano has greater geological significance than the ejection of such enormous quantities of fragmentary matter. In the first place, the fall of these loose materials round the orifice of discharge is one main cause of the growth of the volcanic cone. The heavier fragments gather around the vent, and there too the thickest accumulation of finer dust takes place. Hence, though successive explosions may blow out the upper part of the crater-walls, and prevent the mountain from growing so rapidly in height, every eruption must increase the diameter of the cone. In the second place, as every shower of dust and sand adds to the height of the ground on which it falls, thick volcanic accumulations may be formed far beyond the base of the mountain. The volcano of Sangay, in Ecuador, for instance, has buried the country around it to a depth of 4000 feet under its ashes.[1] In such loose deposits are entombed trees and other kinds of vegetation, together with the bodies of animals, as well as the works of man. In some cases where the layer of volcanic dust is thin, it may merely add to the height of the soil without sensibly interfering with the vegeta-

[1] D. Forbes, *Geol. Mag.* vii. 320.

tion. But it has been observed at Santorin that though this is true in dry weather, the fall of rain with the dust at once acts detrimentally. On the 3rd of June, 1866, the vines were there withered up as if they had been burnt along the track of the smoke cloud.[1] By the gradual accumulation of volcanic ashes new geological formations arise which, in their component materials, not only bear witness to the volcanic eruptions which produced them, but preserve a record of the land-surfaces over which they spread. In the third place, besides the distance to which the fragments may be hurled by volcanic explosions, or to which they may be diffused by the ordinary aerial movements, we have to take into account the vast spaces across which the finer dust is sometimes borne by upper air-currents. In the instance already cited ashes from Coseguina fell 700 miles away, having been carried all that long distance by a high counter-current of air, moving apparently at the rate of about 7 miles an hour in an opposite direction to that of the wind which blew at the surface. By the Sumbawa eruption, also referred to above, the sea west of Sumatra was covered with a layer of ashes two feet thick. On several occasions ashes from one of the Icelandic volcanoes have fallen so thickly between the Orkney and Shetland Islands, that vessels passing there have had the unwonted deposit shovelled off their decks in the morning. In the year 1783, during an eruption of Skaptar-Jökull, so vast an amount of fine dust was ejected that the atmosphere over Iceland continued loaded with it for months afterwards. It fell in such quantity over parts of Caithness—a distance of 600 miles—as to destroy the crops; that year is still spoken of by the inhabitants as the year of "the ashie." Traces of the same deposit have been observed in Norway, and even as far as Holland. Hence it is evident that volcanic accumulations may take place in regions many hundreds of miles distant from any active volcano. A single thin layer of volcanic detritus in a group of sedimentary strata would thus not of itself prove the existence of contemporaneous volcanic action in its neighbourhood. Unsupported by other proof of adjacent volcanic activity, it might be held to have been wind-borne from a volcano in a distant region.

Lava Streams.—At its exit from the side of a volcano, lava glows with a white heat, and flows with a motion which has been compared to that of honey or of melted iron. It soon becomes red, and, like a coal fallen from a hot fireplace, rapidly grows dull as it moves along, until it assumes a black, cindery aspect. At the same time the surface congeals, and soon becomes solid enough to support a heavy block of stone. The aspect of the stream varies with the composition and fluidity of the lava, form of the ground, angle of slope, and rapidity of flow. Viscous lavas, like those of Vesuvius, break upon the surface into rough brown or black cinder-like slags, and irregular ragged cakes, which, with the onward motion, grind and grate against each other with a harsh metallic sound, sometimes

[1] Fouqué, *op. cit.* p. 81.

rising into rugged mounds or getting seamed with rents and gashes, at the bottom of which the red-hot glowing lava may be seen (Fig. 39). In lavas possessing somewhat greater fluidity, the surface presents froth-like, curving lines, as in the scum of a slowly flowing river, or is arranged in curious ropy folds, as the layers have successively flowed over each other and congealed. These, and many other fantastic coiled shapes were exhibited by the Vesuvian lava of 1858. Basalts possessing extreme liquidity have flowed for great distances with singularly smooth surfaces. A large area which has been flooded with lava is perhaps the most hideous and appalling

Fig. 39.—View of portion of a Lava-stream on Vesuvius (Abich).

scene of desolation anywhere to be found on the surface of the globe.

A lava stream usually spreads out as it descends from its point of escape, and moves more slowly. Its sides look like huge embankments, or like some of the long mounds of "clinkers" in a great manufacturing district. The advancing end is often much steeper, creeping onward like a great wall or rampart, down the face of which the rough blocks of hardened lava are ever rattling (Fig. 40).

Outflow of Lava.—This appears to be immediately due to the expansion of the absorbed vapours and gases in the molten rock. Though these vapours may reach the surface and even produce tremendous explosions without an actual outcome of lava, yet so intimately are vapours and lava commingled in the subterranean reservoirs, that they commonly rise together, and the explosions of the one lead to the outflow of the other. The first point at which

the lava makes its appearance at the surface will largely depend upon the structure of the ground. Two causes have been assigned on a foregoing page (p. 213) for the fissuring of a volcanic cone. As the molten mass rises within the chimney of the volcano, continued explosions of vapour take place from its upper surface. The violence of these may be inferred from the vast clouds of steam,

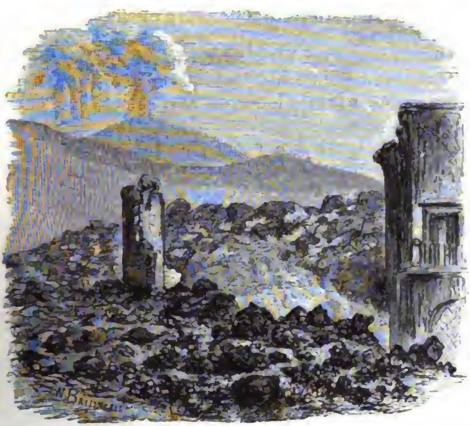

FIG. 40.—VIEW OF HOUSES SURROUNDED AND PARTLY DEMOLISHED BY THE LAVA OF VESUVIUS, 1872.

ashes, and stones hurled to so great a height into the air, and from the concussions of the ground which may be felt at distances of more than 100 miles from the volcano. It need not be a matter of surprise, therefore, that the sides of a great vent exposed to shocks of such intensity should at last give way, and that large divergent fissures should be opened down the cone. Again, the hydrostatic pressure of the column of lava must, at a depth of 1000 feet below the top of the column, exert a pressure of between 70 and 80 tons on each square foot of the surrounding walls. We may well believe that such a force, acting upon the walls of a funnel already shattered by a succession of terrific explosions, will be apt to prove too great for their resistance. When this happens, the lava pours forth from the outside of the cone. On a much fissured cone lava may issue freely from many points, so that a volcano so affected has been graphically described as "sweating fire."

In a lofty volcano lava occasionally rises to the lip of the crater and flows out there; but more frequently it escapes from some fissure or orifice in a weak part of the cone. In minor volcanoes, on the other hand, where the explosions are less violent, and where the

thickness of the cone in proportion to the diameter of the funnel is often greater, the lava very commonly rises into the crater. Should the crater walls be too weak to resist the pressure of the molten mass they give way, and the lava rushes out from the breach. This is seen to have happened in several of the puys of Auvergne, so well figured and described by Scrope (Fig. 41). But if the crater be massive enough to withstand the pressure, the lava, if still impelled upward by the struggling vapour, will at last flow out from the lowest part of the rim.

As soon as the molten rock reaches the surface the superheated water or steam imprisoned within its mass escapes copiously, and hangs as a dense white cloud over the moving current. The lava streams of Vesuvius sometimes appear with as large and dense a steam cloud at their lower ends as that which escapes at the same time from the main crater. Even after the molten mass has

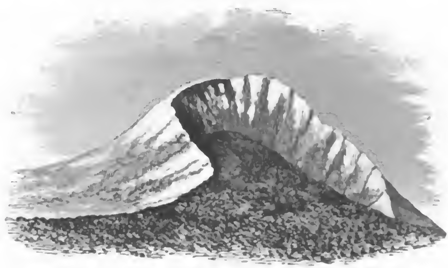

Fig. 41.—View of one of the Tuff Cones of Auvergne, broken down on one Side by the Escape of a Stream of Lava. (After Scrope.

flowed several miles, steam continues to rise abundantly both from its end and from numerous points along its surface, and continues to do so for many weeks, months, or it may be for several years.

Should the point of escape of a lava stream lie well down on the cone, far below the summit of the lava-column in the funnel, the molten rock, on its first escape, driven by hydrostatic pressure, will sometimes spout up high into the air—a fountain of molten rock. This was observed in 1794 on Vesuvius, and in 1832 on Etna. In the eruption of 1852 at Mauna Loa, an unbroken fountain of lava, from 200 to 700 feet in height and 1000 feet broad, burst out at the base of the cone. Similar "geysers" of molten rock have subsequently been noticed in the same region. Thus, in March and April 1868, four fiery fountains, throwing lava to heights varying from 500 to 1000 feet, continued to play for several weeks. According to Mr. Coan, such outbursts take place from the bottom of a column of lava 3000 feet high. The volcano of Mauna Loa strikingly illustrates another feature of volcanic dynamics in the position and outflow of lava. It

bears upon its flanks at a distance of 20 miles, but 10,000 feet lower, the huge crater Kilauea. As Dana has pointed out, these orifices form part of one mountain, yet the column of lava stands 10,000 feet higher in one conduit than in the other. On a far smaller scale the same independence occurs among the several pipes of some of the geysers in the Yellowstone region of North America.

From the wide extent of basalt-dykes, such as those of Britain which rise to the surface at a distance of 200 miles from the main volcanic outbursts of their time, and cover an area of perhaps 100,000 square miles, it is evident that molten lava may sometimes occupy a far greater area within the crust than might be inferred from the dimensions and outpourings even of the largest volcanic cone. There can be no doubt that vast reservoirs of melted rock impregnated with superheated vapours must formerly have existed, if they do not exist still beneath extensive tracts of country (p. 256). Yet even in these more stupendous manifestations of volcanism the lava should be regarded rather as the sign than as the cause of volcanic action. It is the pressure of the imprisoned vapour and its struggles to get free which produce the subterranean earthquakes, explosions, and outpouring of lava. As soon as the vapour finds relief, the terrestrial commotion calms down again, until another accumulation of vapour demands a repetition of the same phenomena.

Rate of flow of Lava.—The rate of movement is regulated by the fluidity of the lava, by its volume, and by the form and inclination of the ground. Hence, as a rule, a lava-stream moves faster at first than afterwards, because it has not had time to stiffen, and its slope of descent is usually steeper than further down the mountain. One of the most fluid and swiftly flowing lava-streams ever observed on Vesuvius was that erupted on 12th August, 1805. It is said to have rushed down a space of 3 Italian ($3\frac{2}{3}$ English) miles in the first four minutes, but to have widened out and moved more slowly as it descended, yet finally to have reached Torre del Greco in three hours. A lava erupted by Mauna Loa in 1852 went as fast as an ordinary stage-coach, or fifteen miles in two hours. Long after a current has been deeply crusted over with slags and rough slabs of lava, it continues to creep slowly forward for weeks or even months.

It happens sometimes that, as the lava moves along, the still molten mass inside bursts through the outer hardened and deeply seamed crust, and rushes out with, at first, a motion much more rapid than that of the main stream. Any sudden change in the form or slope of the ground affects the flow of the lava. Thus, reaching the edge of a steep defile or cliff, the molten rock pours over in a cataract of glowing molten rock, with clouds of steam, showers of fragments, and a noise utterly indescribable. Or on the other hand, encountering a ridge or hill across its path, it accumulates until it either finds egress round the side or actually overrides and entombs the obstacle. The hardened crust or shell within which the still fluid lava moves serves to keep the mass from spreading.

Here and there inside this crust the lava subsides, leaving cavernous spaces and tunnels into which, when the whole is cold, one may creep, and which are sometimes festooned and hung with stalactites of lava.

Size of lava-streams.—In some cases lava escaping from craters or fissures comes to rest before reaching the base of the slopes, like the obsidian current which has congealed on the side of the little volcanic island of Volcano. In other instances the molten rock not only reaches the plains but flows for many miles away from the point of eruption. The most stupendous outpouring of lava on record was that which took place from Skaptar Jökull in Iceland in the year 1783. Successive streams issued from the volcano, flooding the country far and wide, filling up river-gorges which were sometimes 600 feet deep and 200 feet broad, and advancing into the alluvial plains in lakes of molten rock 12 to 15 miles wide and 100 feet deep. Two currents of lava which flowed in nearly opposite directions extended for 45 and 50 miles respectively, their usual thickness being 100 feet, but in narrow defiles reaching sometimes to 600. Bischof estimated that the total amount of lava poured forth during this single eruption "surpassed in magnitude the bulk of Mont Blanc."[1]

Varying liquidity of Lava.—All lava is at the time of its expulsion in a molten condition, that is, consists of a glassy magma in which, by reason of the high temperature, most or all of the mineral constituents exist dissolved. Considerable differences, however, have been observed in the degree of liquidity. Humboldt and Scrope long ago called attention to the thick, short lumpy forms presented by trachytic rocks, which are lighter and more siliceous, and to the thin, widely extended sheets assumed by basalts, which are heavy and contain much iron and basic silicates.[2] It may be inferred that as a rule the basalts or more basic lavas have been more liquid than the trachytes or more siliceous lavas. The cause of this difference has been variously explained. It may depend partly upon chemical composition, the siliceous being naturally less fusible than the basic rocks.

But as great differences of fluidity are observable even among lavas having nearly the same composition, there would seem to be some further cause for the diversity. Reyer has ingeniously maintained that we must look to original differences in the extent to which the subterranean igneous magma which supplied the lava has been saturated with vapours and gases. Molten rock highly impregnated gives rise, he holds, to fragmentary discharges, while when feebly impregnated it flows out tranquilly.[3] On the other hand Captain C. E. Dutton, who has recently studied the volcanic phenomena of Western America, suggests that the different degrees of liquidity may depend, not only on chemical differences, but on

[1] Lyell, *Principles*, ii. p. 49.
[2] Scrope, "Considerations on Volcanoes" (1825), p. 93.
[3] *Beitrag zur Physik der Eruptionen*, p. 77.

variations of temperature. He supposes that the basaltic lavas which have flowed so far in thin sheets, and which must have had a comparatively great liquidity, flowed at temperatures far above that of their melting point, and were, to use his phrase, "superfused."[1]

The varying degrees of liquidity are manifested in a characteristic way on the surface of lava. Thus in the great lava pools of Hawaii the rock exhibits a remarkable liquidity. During its ebullition in the crater-pools, jets and driblets a quarter of an inch in diameter are tossed up, and, falling back on one another, make "a column of hardened tears of lava," one of which (Fig. 42) was

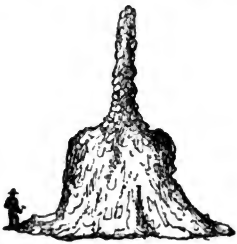

FIG. 42.—COLUMN FORMED OF CONGEALED JETS OF LIQUID LAVA, CRATER OF KILAUEA (DANA).

found to have attained a height of 40 feet, while, in other places, the jets thrown up and blown aside by the wind give rise to long threads of glass which lie thickly together like mown grass, and are known by the natives under the name of Pele's Hair, after one of their divinities.[2]

On the other hand the lavas of Vesuvius and of most modern volcanoes, which issue so saturated with vapour as to be nearly concealed from view in a cloud of steam, are accompanied by abundant explosions of fragmentary materials. Slags and clinkers, torn by explosions of steam from the molten rock, are strewn abundantly over the cone, while the surface of the lava is likewise rugged with similar clinkers, which may now and then be observed piled up round some more energetic steam spiracle (Fig. 43). So vast an amount of steam rushes out from one of these orifices and with such boiling and explosion that the cone of bombs, slags, and irregular lumps of lava, forms a miniature or parasitic volcano, which will remain as a marked cone on its parent mountain long after the eruption which gave it birth has ceased. The lava of the eruption at Santorin in 1866–67 at first welled out tranquilly, but after a few days its outflow was accompanied with explosions and discharges of incandescent fragments, which increased until they had covered the

[1] "High Plateaux of Utah," *Geog. and Geol. Survey of Territories.* Washington, 1880, chap. v.
[2] Dana, *Geol. U. S. Explor. Exped.*, p. 179.

lava dome with ejected scoriæ, and had opened a number of crateriform mouths on its summit.[1]

There can be no doubt, as above remarked, that the condition of liquidity of the lava has in some measure determined the form of the eruptions. In one case there are quiet out-wellings of the more liquid lavas, as at Hawaii; in another there are explosive discharges and cinder cones accompanying the more viscid lavas, as at most modern volcanoes. The former has been the condition

Fig. 43.—Lava Column (eight feet high), Vesuvius (Abich).

favourable to the most colossal outpourings of molten rock, as we see in the basalt plateaux of Britain, Faroe, Greenland, Idaho, and Oregon, the Ghauts, Abyssinia, &c. This subject is again referred to at p. 256.

Crystallization of Lava.—Pouring forth with a liquidity like that of molten iron, lava speedily assumes a more viscous condition and a slower motion. Obsidian and other vitreous rocks have consolidated as glass. Yet that they are not always extremely fluid is indicated by the arrest of the obsidian stream half way down the steep northern slope of Volcano. Even in such perfect natural glass as obsidian,

[1] Fouqué, *op. cit.* p. xv.

microscopic crystallites and crystals are usually present and sometimes in prodigious numbers (pp. 104, 141). In most lavas devitrification has proceeded so far before the final stiffening that the original glassy magma has passed into a more or less completely lithoid or crystalline mass.

That lava may possess an appreciably crystalline structure while still in motion has often been proved at Vesuvius, where well-defined crystals of the infusible leucite may be observed in a molten magma of the other minerals, portions of the white-hot rock in this condition being ladled out, impressed with a stamp and suddenly congealed. The fluxion structure above (p. 104) described, furnishes interesting evidence of this fact in many ancient as well as modern lavas.

The crystalline structure appears to be developed in lava under some pressure and in presence of the volcanic vapours and gases with which the molten rock is impregnated. The rapid escape of these vapours may prevent the formation of the crystalline structure and leave the lava in the condition of a more or less perfect glass. This may perhaps be the explanation of the vitreous crust on the walls of dykes already (pp. 105, 214) referred to. Rocks crystallizing in the deeper parts of a volcano appear usually to possess a more coarsely crystalline structure than those which crystallize near the surface.

Temperature of Lava.—It would be of the highest interest and importance to know accurately the temperature at which a lava stream first issues. Measurements not altogether satisfactory have been taken at various distances below the point of emission where the moving lava could be safely approached. Experiments made at Vesuvius by Scacchi and Sainte-Claire Deville in 1855, by thrusting thin wires of silver, iron, and copper into the lava, indicated a temperature of scarcely 700° C. (1228° Fahr.) Observations of a similar kind, made in 1819, when a silver wire $\frac{1}{30}$th inch in diameter at once melted in the Vesuvian lava of that year, gave a greatly higher temperature, the melting point of silver being about 1800° Fahr. But copper wire has also been melted, the point of fusion of this metal being about 2204° Fahr. Evidence of the high temperature of lava has likewise been adduced from the alteration it has effected upon refractory substances in its progress, as where, at Torre del Greco, it overflowed the houses, and was afterwards found to have fused the fine edges of flints, to have decomposed brass into its component metals, the copper actually crystallizing, and to have melted silver, and even sublimed it into small octahedral crystals. The lava of Santorin has caught up pieces of limestone, and has formed out of them nodules containing crystallized anorthite, augite, sphene, black garnet, and particularly wollastonite.[1] The initial temperature of lava, as it first issues from the Vesuvian funnel, is probably considerably more than 2000° Fahr. Obviously the absorbed water in the white-hot lava must possess as high a temperature. The existence of white-hot water, even in rocks

[1] Fouqué, *op. cit.* p. 206.

which have reached the surface, is a fact of no little significance in the theoretical consideration of hypogene action.

Inclination of lava-flows.—It was at one time supposed that lava could not consolidate in beds on such steep slopes as those of most volcanoes. Hence arose the "elevation-crater theory" (described at p. 240), in which the inclined position of lavas round a volcanic vent was explained by upheaval after their emission. Observations all over the world, however, have now demonstrated that lava, with all its characteristic features, can consolidate on slopes of even 35° and 40°. The lava in the Hawaii Islands has cooled rapidly on slopes of 25°, that from Vesuvius, in 1855, is here and there as steep as 30°, while the older lavas in Monte Somma are sometimes inclined at 45°. On the east side of Etna, a cascade of lava, which poured in 1689, into the vast hollow of the Cava Grande, has an inclination varying from 18° to 48°, with an average thickness of 16 feet. On Mauna Loa some lava-flows are said to have congealed on slopes of 49°, 60°, and even 80°, though in these cases it could only be a layer of rock stiffening and adhering to the surface of the declivity. Even when it consolidates on a steep slope, a stream of lava forms a sheet with parallel upper and under surfaces, a general uniformity of thickness, and often greater evenness of surface than where the angle of descent is low. The thickness varies indefinitely; many basalts which have been poured out in a remarkably liquid condition have solidified in beds not more than 10 or 12 feet thick. On the other hand more pasty lavas, especially where they have flowed into narrow valleys, may be piled up into solid masses to a thickness of several hundred feet.

Structure of a lava-stream.—Some lava-streams are nearly homogeneous throughout. In general, however, they each show three component layers. At the bottom lies a rough, slaggy mass, produced by the rapid cooling of the lava, and the breaking up and continued onward motion of the scoriform layer. The central and main portion of the stream consists of solid lava, often, however, with a more or less carious and vesicular texture. The upper part, as we have seen, may be a mass of rough broken-up slabs, scoriæ, or clinkers. The proportions borne by these respective layers to each other vary continually. Some of the more fluid ropy lavas of Vesuvius have an inconstant and thin slaggy crust; others may be said to consist of little else than scoriæ from top to bottom. Throughout the whole mass of a lava-current, but more especially along its upper surface, the absorbed vapours expand as the pressure diminishes, and pushing the molten rock aside, segregate into small bubbles or irregular cavities. Hence, when the lava solidifies, these steam-holes are seen to be sometimes so abundant that a detached portion of the rock containing them will float in water (pumice). They are often elongated in the direction of the motion of the lava-stream (Fig. 44). Sometimes, indeed, where the cells are numerous, this elongation of them in one direction gives a fissile structure to the rock.

In passing from a fluid to a solid condition, and thus contracting, lava acquires different structures. Lines of divisional planes or joints traverse it, especially perpendicular to the upper and under surfaces of the sheet. These sometimes assume prismatic forms,

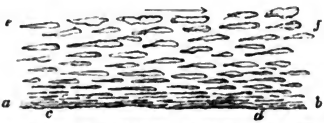

FIG. 44.—ELONGATION OF VESICLES IN DIRECTION OF FLOW OF LAVA.

dividing the rock into columns, as is so frequently to be observed in basalt. They are described in Book IV. Part ii., together with other forms of joints.

Vapours and sublimations of a lava-stream.—Besides steam, many other vapours absorbed in the original subterranean molten magma escape from fissures of a lava-stream. The points at which such vapours are copiously disengaged are termed *fumaroles.* Among the exhalations, chlorides abound, particularly chloride of sodium, which appears, not only in fissures, but even over the cooled crust of the lava, in small crystals, in tufts, or as a granular and even glassy incrustation. Chloride of iron is deposited as a yellow coating at fumaroles, where also bright emerald green films and scales of chloride of copper may be more rarely observed. Many chemical changes take place in the escape of these vapours. Thus specular-iron, either the result of the mutual decomposition of steam and iron chloride, or of the oxidation of magnetite, forms abundant scales, plates, and small crystals in the fumaroles and vesicles of some lavas. Sal-ammoniac also appears in large quantity on many lavas, not merely in the fissures, but also on the upper surface. This salt is not directly a volcanic product, but results from some decomposition, probably from that of the aqueous vapour, whereby a combination is formed with atmospheric nitrogen.

Slow cooling of lava.—The hardened crust of a lava-stream is a bad conductor of heat. Consequently, the surface of the stream may have become cool enough to be walked upon, though the red-hot mass may be observed through the rents to lie only a few inches below. Many years therefore may elapse before the temperature of the whole mass has fallen to that of the surrounding soil. Eleven months after an eruption of Etna, Spallanzani could see that the lava was still red-hot at the bottom of the fissures, and a stick thrust into one of them instantly took fire. The Vesuvian lava of 1785 was found by Breislak seven years afterwards to be still hot and steaming internally, though lichens had already taken root on its surface. The ropy lava erupted by Vesuvius in 1858 was observed by the author in 1870 to be still so hot, even near its termination, that steam issued abundantly from its rents, many of which were too

warm to allow the hand to be held in them, and three years later it was still steaming abundantly. Hoffmann records that from the lava which flowed from Etna in 1787 steam was still issuing in 1830. Yet more remarkable is the case of Jorullo, in Mexico, which sent out lava in 1759. Twenty-one years later a cigar could be lighted at its fissures: after 44 years it was still visibly steaming; and even in 1846, that is, after 87 years of cooling, two vapour columns were still rising from it.[1]

This extremely slow rate of cooling has justly been regarded as a point of high geological significance in regard to the secular cooling and probable internal temperature of our globe. Some geologists have argued indeed that, if so comparatively small a portion of molten matter as a lava-stream can maintain a high temperature under a thin, cold crust for so many years, we may, from analogy, feel little hesitation in believing that the enormously vaster mass of the globe may, beneath a relatively thin crust, still continue in a molten condition within. More legitimate deductions, however, might be drawn from more accurate and precise measurements of the rate of loss of heat, and of its variations in different lava-streams. Sir William Thomson, for instance, has suggested that, by measuring the temperature of intrusive masses of igneous rock in coal-workings and elsewhere, and comparing it with that of other non-volcanic rocks in the same regions, we might obtain data for calculating the time which has elapsed since these igneous sheets were erupted (*ante*, p. 46).

Effects of lava-streams on superficial waters and topography.—In its descent a stream of lava may reach a watercourse, and, by throwing itself as an embankment across the stream, may pond back the water and form a lake. Such is the origin of the picturesque Lake Aidat in Auvergne. Or the molten current may usurp the channel of the stream, and completely bury the whole valley, as has happened again and again among the vast lava-fields of Iceland. Few changes in physiography are so rapid and so enduring as this. The channel which has required, doubtless, many thousands of years for the water laboriously to excavate, is sealed up in a few hours under 100 feet or more of stone, and another vastly protracted interval may elapse before this newer pile is similarly eroded.[2]

By suddenly overflowing a brook or pool of water, molten lava sometimes has its outer crust shattered to fragments by a sharp explosion of the generated steam, while the fluid mass within rushes out on all sides. The lavas of Etna and Vesuvius have protruded into the sea. Thus a current from the latter mountain entered the Mediterranean at Torre del Greco in 1794, and pushed its way for 360 feet outwards, with a breadth of 1100 and a height of 15 feet. So

[1] E. Schleiden, quoted by Naumann, *Geol.* i. p. 160.

[2] For an example of the conversion of a lava-buried river-bed into a hill-top by long-continued denudation, see *Quart. Journ. Geol. Soc.* 1871, p. 303.

quietly did it advance that Breislak could sail round it in a boat and observe its progress.

By the outpouring of lava two important kinds of geological change are produced. (1) Stream-courses, lakes, ravines, valleys, in short all the minor features of a landscape, may be completely overwhelmed under a thick sheet of lava. The drainage of the district being thus effectually altered, the numerous changes which flow from the operations of running water over the land are arrested and made to begin again in new channels. (2) Considerable alterations may likewise be caused by the effects of the heat and vapours of the lava upon the subjacent or contiguous ground. Instances have been observed in which the lava has actually melted down opposing rocks, or masses of slags on its own surface. Interesting observations, already referred to, have been made at Torre del Greco under the lava-stream which overflowed part of that town in 1794. It was found that the window-panes of the houses had been devitrified into a white, translucent, stony substance; that pieces of limestone had acquired an open, sandy, granular texture, without loss of carbon dioxide, and that iron, brass, lead, copper, and silver objects had been greatly altered, some of the metals being actually sublimed. We can understand, therefore, that, retaining its heat for so long a time, a mass of lava may induce many crystalline structures, rearrangements, or decompositions in the rocks over which it comes to rest, and proceeds slowly to cool. This is a question of considerable importance in relation to the behaviour of ancient lavas which have been intruded among rocks beneath the surface, and have subsequently been exposed (Book IV. Part VII.).

But on the other hand, the exceedingly trifling change produced, even by a massive sheet of lava, has often been remarked with astonishment. On the flank of Vesuvius vines and trees may be seen still flourishing on little islets of the older land surface, completely surrounded by a flood of lava. Dana has given an instructive account of the descent of a lava-stream from Kilauea in June 1840. Islet-like spaces of forest were left in the midst of the lava, many of the trees being still alive. Where the lava flowed round the trees the stumps were usually consumed, and cylindrical holes or casts remained in the lava, either empty or filled with charcoal. In many cases the fallen crown of the tree lay near, and so little damaged that the epiphytic plants on it began to grow again. Yet so fluid was the lava that it hung in pendent stalactites from the branches, which nevertheless, though clasped round by the molten rock, had barely their bark scorched. Again, for nearly 100 years there has lain on the flank of Etna a large sheet of ice, which, originally in the form of a thick mass of snow, was overflowed by lava and has thereby been protected from the evaporation and thaw which would certainly have dissipated it long ago, had it been exposed to the air. The heat of the lava has not sufficed to melt it. In other cases snow and ice have been melted in large quantities by overflowing lava.

The great floods of water which rushed down the flank of Etna, after an eruption of the mountain in the spring of 1755, and similar deluges at Cotopaxi, are thus explained.

One further aspect of a lava-stream may be noticed here—the effect of time upon its surface. While all kinds of lava must, in the end, crumble down under the influence of atmospheric waste and, where other conditions permit, become coated with soil and support some kind of vegetation, yet extraordinary differences may be observed in the facility with which different lava-streams yield to this change, even on the flank of the same mountain. Every one who ascends the slopes of Vesuvius remarks this fact. After a little practice it is not difficult there to trace the limits of certain lavas even from a distance, in some cases by their verdure, in others by their barrenness. Five hundred years have not sufficed to clothe with green the still naked surface of the Catanian lava of 1381; while some of the lavas of the present century have long given footing to bushes of furze. Some of the younger lavas of Auvergne, which certainly flowed in times anterior to those of history, are still singularly bare and rugged. Yet, on the whole, where lava is directly exposed to the atmosphere, without receiving protection from occasional showers of volcanic ash, or where liable to be washed bare by heavy torrents of rain, its surface decays in a few years sufficiently to afford soil for stray plants in the crevices. When these have taken root they help to increase the disintegration; at last, as the rock is overspread, the traces of its volcanic origin fade away from its surface. Some of the Vesuvian lavas of the present century already support vineyards.

Subsidence and Elevation.—Proofs of elevation are frequent among volcanic vents which, lying near the sea and containing marine sediments among their older erupted materials, supply in the enclosed marine organisms evidence of the movement. In this way it is known that Etna, Vesuvius and other Mediterranean volcanoes, began their history as submarine vents, and that they owe their present dimensions not only to the accumulation of ejected materials, but also to some extent to an elevation of the sea-bottom. Proof of subsidence is less easily traced, but indications have been observed of a sinking of the ground beneath a volcanic vent, as if the crust had settled down upon the cavity made by the discharge of so much volcanic material. During the recent eruption of Santorin, very decided but extremely local subsidence took place near the vent in the centre of the old crater.

Torrents of Water and Mud.—We have seen that large quantities of water accompany many volcanic eruptions. In some cases, where ancient crater-lakes or internal reservoirs, shaken by repeated detonations, have been finally disrupted, the mud which has thereby been liberated issues at once from the mountain. Such "mud-lava," (*lava d' aqua*), on account of its liquidity and swiftness of motion, is more dreaded for destructiveness than even the true

melted lavas. On the other hand, rain or melted snow or ice, rushing down the cone and taking up loose volcanic dust, is converted into a kind of mud that grows more and more pasty as it descends. The mere sudden rush of such large bodies of water down the steep declivity of a volcanic cone cannot fail to effect much geological change. Deep trenches are cut out of the loose volcanic slopes, and sometimes large areas of woodland are swept away, the débris being strewn over the plains below.

It was one of these mud-lavas which invaded Herculaneum during the great eruption of 79, and which, quickly enveloping the houses and their contents, has preserved for us so many precious and perishable monuments of antiquity. In the same district during the eruption of 1622 a torrent of this kind poured down upon the villages of Ottajano and Massa, overthrowing walls, filling up streets, and even burying houses with their inhabitants. During the great eruption of Cotopaxi in June 1877 enormous torrents of water and mud, produced by the melting of the snow and ice of the cone, poured down from the mountain. Among the débris hurried along were vast numbers of large blocks of ice. The villages all round the mountain to a distance of sometimes more than ten geographical miles were left deeply buried under a deposit of mud mixed with blocks of lava, ashes, pieces of wood, &c.[1] Many of the volcanoes of Central and South America discharge large quantities of mud directly from their craters. Thus in the year 1691 Imbaburu, one of the Andes of Quito, emitted floods of mud so largely charged with dead fish that pestilential fevers arose from the subsequent effluvia. Seven years later (1698), during an explosion of another of the same range of lofty mountains, Carguairazo (14,706 feet), the summit of the cone is said to have fallen in, while torrents of mud, containing immense numbers of the fish *Pymelodus Cyclopum*, poured forth and covered the ground over a space of four square leagues. The carbonaceous mud (locally called *moya*) emitted by the Quito volcanoes sometimes escapes from lateral fissures, sometimes from the craters. Its organic contents, and notably its siluroid fish, which are the same as those found living in the streams above ground, prove that the water is derived from the surface, and accumulates in craters or underground cavities until discharged by volcanic action. Similar but even more stupendous and destructive outpourings have taken place from the volcanoes of Java, where wide tracts of luxuriant vegetation have at different times been buried under masses of dark grey mud, sometimes 100 feet thick, with a rough hillocky surface from which the top of a submerged palm-tree occasionally protruded.

Between the destructive effects of mere water-torrents and that of these mud-floods there is, of course, the notable difference that, whereas in the former case a portion of the surface is swept away, in the latter, while sometimes considerable demolition of the surface takes place at first, the main result is the burying of the ground

[1] Wolf, *Neues Jahrb.* 1878, p. 133.

under a new tumultuous deposit by which the surface is greatly changed, not only as regards its temporary aspect, but in its more permanent features, such as the position and form of its water-courses.

Mud-Volcanoes.—These are of two kinds: 1st, where the chief source of movement is the escape of gaseous discharges; 2nd, where the active agent is steam.

(1) Although not volcanic in the proper sense of the term, certain remarkable orifices of eruption may be noticed here, to which the names of *mud-volcanoes, salses, air-volcanoes,* and *macalubas* have been applied. These are conical hills formed by the accumulation of fine and usually saline mud, which, with various gases, is continuously or intermittently given out from the orifice or crater in the centre. They occur in groups, each hillock being sometimes less than a yard in height, but ranging up to elevations of 100 feet or more. Like true volcanoes, they have their periods of repose, when either no discharge takes place at all, or mud oozes out tranquilly from the crater, and their epochs of activity, when large volumes of gas, and sometimes columns of flame, rush out with considerable violence and explosion, and throw up mud and stones to a height of several hundred feet. The gases play much the same part, therefore, in these phenomena that steam does in those of true volcanoes. They consist of carbon dioxide, carburetted hydrogen, sulphuretted hydrogen, and nitrogen. The mud is usually cold. In the water occur various saline ingredients, among which common salt generally appears; hence the name, *Salses*. Naphtha is likewise frequently present. Large pieces of stone, differing from those in the neighbourhood, have been observed among the ejections, indicative doubtless of a somewhat deeper source than in ordinary cases. Heavy rains may wash down the minor mud-cones and spread out the material over the ground, but gas-bubbles again appear through the sheet of mud, and by degrees a new series of mounds is once more thrown up.

There can be little doubt that this type of mud-volcano is to be traced to chemical changes in progress underneath. Dr. Daubeny explained them in Sicily by the slow combustion of beds of sulphur. The frequent occurrence of naphtha and of imflammable gas points, in other cases, to the disengagement of hydrocarbons from subterranean strata.

(2) The second class of mud-volcano presents itself in true volcanic regions, and is due to the escape of hot water and steam through beds of tuff or some other friable kind of rock. The mud is kept in ebullition by the rise of steam through it. As it becomes more pasty and the steam meets with greater resistance, large bubbles are formed, which burst, and the more liquid mud from below oozes out from the vent. In this way small cones are built up, many of which have perfect craters atop. In the Geyser tracts of the Yellowstone region there are several instructive examples of such active and extinct mud-vents. Some of the extinct cones there are not

more than a foot high, and might be carefully removed as museum specimens.

Mud-volcanoes occur in Iceland, Sicily (Macaluba), in many districts of northern Italy, at Tamar and Kertch, at Baku on the Caspian, near the mouth of the Indus, and in other parts of the globe.[1]

Exhalations of Vapours and Gases.—In volcanic districts, sometimes from the craters and sides of dormant or extinct cones, sometimes at a distance from them, heated vapours and gases are given off from orifices continuously and without eruptive discharges. Numerous examples occur among the volcanic tracts of Italy, where they have been termed *suffioni*. Steam, sulphuretted hydrogen, hydrochloric acid, and carbonic acid are particularly noticeable at these orifices. The vapours in rising condense. The sulphuretted hydrogen becomes sulphuric acid, which powerfully corrodes the surrounding rocks. The lava or tuff through which the hot vapours rise is bleached into a white or yellowish crumbling clay, in which, however, the less easily corroded crystals may still be recognised *in situ*. At the same time, sublimates of sulphur or of chlorides may be formed, or the sulphuric acid attacking the lime of the silicates gives rise to gypsum, which spreads in a network of threads and veins through the hot, steaming, and decomposed mass. In this way at the island of Volcano, obsidian is converted into a snow-white, dull, clay-stone-like substance, with crystals of sulphur and gypsum in its crevices. Silica is likewise deposited from solution at many orifices, and coats the altered rock with a crust of calcedony, hyalite, or some form of siliceous sinter. As the result of this action masses of rock are decomposed below the surface, and new deposits of alum, sulphur, sulphides of iron and copper, &c., are formed above them. Examples have been described from Iceland, Lipari, Hungary, Terceira, Teneriffe, St. Helena, and many other localities.[2]

Another class of gaseous emanations betokens a condition of volcanic activity further advanced towards final extinction. In these the gas is carbon dioxide, either issuing directly from the rock or bubbling up with water which is often quite cold. The old volcanic districts of Europe furnish many examples. Thus on the shores of the Laacher See—an ancient crater lake of the Eifel—the gas issues from numerous openings called *moffette*, round which dead insects, and occasionally mice and birds, may be found. In the same region occur hundreds of springs more or less charged with this gas. The famous Valley of Death in Java contains one of

[1] On mud-volcanoes, see Bunsen, *Liebig's Annal*, lxiii. (1847), p. 1; Abich, *Mem. Acad. St. Petersburg*, 7e sér. t. vi. No. 5, ix. No. 4; Daubeny's *Volcanoes*, pp. 264, 539; Buist, *Trans. Bombay Geograph. Soc.* x. p. 154; Roberts, *Journ. Roy. Asiatic Soc.*, 1850; De Verneuil, *Mem. Soc. Geol. France*, iii. (1838), p. 4; Stiffe, *Q. J. Geol. Soc.* xxx. p. 50; Von Lasaulx, *Z. Deutsch. Geol. Ges.* xxxi. p. 457; Gümbel, *Sitzb. Akad. Münch.* 1879.

[2] Von Buch, "Canar. Inseln," 232. Hoffman, *Pogg. Ann.* 1832, pp. 38, 40, 60. Bunsen, *Ann. Chem. Pharm.* 1847 (lxii.), p. 10. Darwin, "Volcanic Islands," p. 29.

the most remarkable gas springs in the world. It is a deep, bosky hollow, from one small space on the bottom of which carbon dioxide issues so copiously as to form the lower stratum of the atmosphere. Tigers, deer, and wild-boar, enticed by the shelter of the spot, descend and are speedily suffocated. Many of their skeletons, together with those of man himself, have been observed.

As a distinct class of gas-springs we may group and describe here the emanations of volatile hydrocarbons, which, when they take fire, are known as Fire-wells. These are not of volcanic origin, but arise from changes within the solid rocks underneath. They occur in many of the districts where mud-volcanoes appear, as in northern Italy, on the Caspian, in Mesopotamia, in southern Kurdistan, and in many parts of the United States. It has been observed that they frequently rise in regions where beds of rock-salt lie underneath, and as that rock has been ascertained often to contain compressed gaseous hydrocarbons, the solution of the rock by subterranean water, and the consequent liberation of the gas, has been offered as an explanation of these fire-wells.

In the oil regions of Pennsylvania certain sandy strata occur at various geological horizons whence large quantities of petroleum and gas are obtained. In making the borings for oil-wells, reservoirs of gas as well as subterranean courses or springs of water are met with. When the supply of oil is limited but that of gas is large, a contest for possession of the bore-hole sometimes takes place between the gas and water. When the machinery is removed and the boring is abandoned, the contest is allowed to proceed unimpeded and results in the intermittent discharge of columns of water and gas to heights of 130 feet or more. At night, when the gas has been lighted, the spectacle of one of these "fire-geysers" is inconceivably grand.[1]

Geysers.—In some regions where volcanic action still continues, and in others where it has long been dormant, there occur eruptive fountains of hot water and steam, to which the general name of Geysers (*i.e.* gushers) is given, from the examples in Iceland, which were the first to be seen and described. The Great and Little Geysers, the Strokkr, and other minor springs of hot water in Iceland, have long been celebrated. More recently another series has been discovered in New Zealand. But probably the most remarkable and numerous assemblage is that which within the last decade has been brought to light in the north-west part of the territory of Wyoming, and which has been included within the "Yellowstone National Park"—a region set apart by the Congress of the United States to be for ever exempt from settlement, and to be retained for the instruction of the people. In this singular region

[1] Ashburner, *Proc. Amer. Phil. Soc.*, xvii. (1877), p. 127. *Stowell's Petroleum Reporter.* 15th Sept. 1879. *Second Geol. Survey of Pennsylvania.* Reports by J. Carll, 1877, 1880. On the naphtha districts of the Caspian Sea, Abich, *Jahrb. Geol. Reichs.* xxix. (1879), p. 165; see also for phenomena in Gallicia the same work, xv. pp. 199, 351; xvii. p. 291; xviii. p. 311.

the ground in certain tracts is honeycombed with passages which communicate with the surface by hundreds of openings, whence boiling water and steam are emitted. In most cases, the water remains clear, tranquil, and of a deep green-blue tint, though many of the otherwise quiet pools are marked by patches of rapid ebullition. These pools lie on mounds or sheets of sinter, and are usually edged round with a raised rim of the same substance, often beautifully fretted and streaked with brilliant colours. The eruptive openings usually appear on small, low, conical elevations of sinter, from each of which one or more tubular projections rise. It is from these irregular tube-like excrescences that the eruptions take place.

The term geyser is restricted to active openings whence columns of hot water and steam are from time to time ejected; the non-eruptive pools are only hot springs. A true geyser should thus possess an underground pipe or passage, terminating at the surface in an opening built round with deposits of sinter. At more or less regular intervals rumblings and sharp detonations in the pipe are followed by an agitation of the water in the basin, and then by the violent expulsion of a column of water and steam to a considerable height in the air. In the upper Fire-hole basin of the Yellowstone Park one of the geysers, named "Old Faithful" (Fig. 45), has ever

FIG. 45.—VIEW OF OLD FAITHFUL GEYSER, AND OTHERS IN THE DISTANCE, FIRE HOLE RIVER, YELLOWSTONE PARK.

since the discovery of the region, sent out a column of mingled water and steam every sixty-three minutes or thereabouts. The column rushes up with a loud roar to a height of more than 100 feet, the whole eruption not occupying more than about five or six minutes. The other geysers of the same district are more capricious in their movements, and some of them more stupendous in the volume of their discharge. The

eruptions of the Castle, Giant, and Beehive vents are marvellously impressive.[1]

In examining the Yellowstone geyser region in 1879 the author was specially struck by the evident independence of the vents. This was shown by their very different levels, as well as by their capricious and unsympathetic eruptions. On the same hill-slope dozens of quiet pools, as well as some true geysers, were noticed at different levels, from the edge of the Fire Hole River up to a height of at least 80 feet above it. Yet the lower pools, from which, of course, had there been underground connection between the different vents, the drainage should have principally discharged itself, were often found to be quiet steaming pools without outlet, while those at higher points were occasionally in active eruption. It seemed also to make no difference in the height or tranquillity of one of the quietly boiling cauldrons, when an active projection of steam and water was going on from a neighbouring vent on the same gentle slope.

Bunsen and Descloiseaux spent some days experimenting at the Icelandic geysers, and ascertained that in the Great Geyser, while the surface temperature is about 212° Fahr., that of lower portions of the tube is much higher—a thermometer giving as high a reading as 266° Fahr.[2] The water at a little depth must consequently be 54° above the normal boiling-point, but it is kept in the fluid state by the pressure of the overlying column. At the basin, however, the water cools quickly. After an explosion it accumulates there, and eventually begins to boil. The pressure on the column below being thus relieved, a portion of the superheated water flashes into steam, and as the change passes down the pipe, the whole column of water and steam rushes out with great violence. The water thereafter gradually collects again in the pipe, and after an interval of some hours the operation is renewed. The experiments made by Bunsen proved the source of the eruptive action to lie in the hot part of the pipe. He hung stones by strings to different depths in the funnel of the geyser, and found that only those in the higher part were cast out by the rush of water, sometimes to a height of 100 feet, while at the same time the water at the bottom was hardly disturbed at all. These observations give much interest and importance to the phenomena of geysers in relation to volcanic action. They show that the eruptive force is steam; that the water column, even at a comparatively small depth, may have a temperature considerably above 212°; that this high temperature is local; and that the eruptions of steam and water take place periodically, and with such vigour as to eject large stones to a height of 100 feet.

The hot water comes up with a considerable percentage of mineral matter in solution. According to the analysis of Sandberger, water

[1] See Hayden's Report for 1870; Comstock's Report in Jones's Reconnaissance of N. W. Wyoming, &c., 1874.

[2] *Comptes Rendus*, xxiii. (1846), p. 934; *Pogg. Annal.* lxxii. (1847), p. 159; lxxxiii. (1851), p. 197. *Ann. Chimie*, xxxviii. (1853), pp. 215, 385.

from the Great Geyser of Iceland contains in 10,000 parts the following proportions of ingredients: silica 5·097, sodium carbonate 1·939, ammonium carbonate 0·083, sodium sulphate 1·07, potassium sulphate 0·475, magnesium sulphate 0·042, sodium chloride 2·521, sodium sulphide 0·088, carbonic acid 0·557, = 11·872.[1]

As soon as the water reaches the surface and begins both to cool and to evaporate it deposits the silica as a sinter on the surfaces over which it flows or on which it rests. The deposit naturally takes place fastest along the margins of the pools. Hence the curiously fretted rims by which these sheets of water are surrounded, and the tubular or cylindrical protuberances which rise from the growing domes.

In course of time the network of underground passages undergoes alteration. Orifices that were once active cease to erupt, and even the water fails to overflow them. Sinter is no longer formed round them, and their surfaces, exposed to the weather, crack into fine shaly rubbish like comminuted oyster-shells. Or the cylinder of sinter grows upward until, by the continued deposit of sinter and the failing force of the geyser, the tube is finally filled up, and then a dry and crumbling white pillar is left to mark the site of the extinct geyser.

§ 3. Structure of Volcanoes.

We have now to consider the manner in which the various solid materials ejected by volcanic action are built up at the surface. This inquiry will be restricted here to the phenomena of modern volcanoes, including the active and dormant or recently extinct phases. Obviously, however, in a modern volcano we can study only the upper and external portions, the deeper and fundamental parts being still concealed from view. The interior structure has been in many cases laid open among the volcanic products of ancient vents. As these belong to the architecture of the terrestrial crust they are described in Book IV. The student is therefore requested to take the descriptions there given in connection with the foregoing and present sections as related chapters of the study of vulcanism.

Confining attention at present to modern volcanic action, we find that the solid materials emitted from the earth's interior are arranged in two distinct types of structure, according as the eruptions proceed from local orifices or from an extensive system of fissures. In the former case volcanic cones are produced; in the latter volcanic plateaux or plains. The type of the volcanic cone or ordinary volcano is now the most abundant and best known.

i. *Volcanic Cones.*

From some weaker point of a fissure, or from a vent opened directly by explosion, volcanic discharges of gases and vapours with

[1] Annal. Chem. und Pharm. 1847, p. 49.

their liquid and solid accompaniments make their way to the surface and gradually build up a volcanic hill or mountain. Occasionally eruptions have proceeded no further than the first stage of gaseous explosion. A cauldron-like cavity has been torn open in the ground, and ejected fragments of the solid rocks through which the explosion has emerged have fallen back into and round the vent. Subsequently, after possible subsidence of the fragmentary materials in the vent, and even of the sides of the orifice, water supplied by rain and filtering from the neighbouring ground has partially, or wholly, filled up the cavity. In this way a lake has arisen either with or without a superficial outlet. Under favourable circumstances, vegetation creeping over bare earth and stone, may so conceal all evidence of the original volcanic action as to make the quiet sheet of water look as if it had always been an essential part of the landscape. Explosion lakes of this kind occur in districts of extinct volcanoes as in the Eifel (*maare*), central Italy, and Auvergne. A remarkable example is supplied by the Lonar Lake in the Indian peninsula, half-way between Bombay and Nágpúr. It lies in the midst of the volcanic plateau of the Deccan traps, which extend around it for hundreds of miles in nearly flat beds that slightly dip away from the lake. An almost circular depression, rather more than a mile in diameter, and from 300 to 400 feet deep, contains at the bottom a shallow lake of bitter saline water, depositing crystals of trona (sesquicarbonate of soda). Except to the north and north-east, it is encircled with a raised rim of irregularly piled blocks of basalt, identical with that of the beds through which the cavity has been opened. The rim never exceeds 100 feet, and is often not more than 40 or 50 feet in height, and cannot contain a thousandth part of the material which once filled the crater. No other evidence of volcanic discharge from this vent is to be seen. Some of the contents of the cavity may have been ejected in finer particles, which have subsequently been removed by denudation; but it seems more probable that the existence of the cavity is mainly due to subsidence after the original explosion.[1]

In most cases explosions are accompanied by the expulsion of so much solid material that a cone gathers round the point of emission. As the cone increases in height by successive additions of ashes or lava to its surface, these volcanic sheets are laid down upon progressively steeper slopes. The inclination of beds of lava, which must have originally issued in a more or less liquid condition, offered formerly a difficulty to observers, and suggested the famous theory of Elevation-craters (*Erhebungskratere*) of L. von Buch,[2] E. de Beaumont,[3] and other geologists. According to this theory the conical shape of a volcanic cone arises mainly from an upheaval or swelling of the

[1] On explosion-craters and lakes, see Scrope's *Volcanoes*. Lecoq, *Epoques Géologiques de l'Auvergne*, tome iv.; compare also Vogelsang, *Vulcane der Eifel*, and in *Neues Jahrb.* 1870, pp. 199, 326, 460. On Lonar Lake, see Malcolmson, *Trans. Geol. Soc.* 2nd ser., v. p. 562. Medlicott and Blandford's "Geology of India," p. 379.

[2] *Pogg. Ann.* ix., x., xxxvii. p. 169.

[3] *Bull. Soc. Géol. France*, iv. p. 357. *Ann. des Mines*, ix. and x.

ground round the vent from which the materials are finally expelled. A portion of the earth's crust (represented in Fig. 46 as composed of stratified deposits, *a b g h*) was believed to have been pushed up like a huge blister, by forces acting from below (at *c*) until the summit of the dome gave way and volcanic materials were emitted. At first these might only partially fill the cavity (as at *f*), but subsequent eruptions, if sufficiently copious, would cover over the truncated edges of the pre-volcanic rocks (as at *g* and *h*), and would be liable to further upheaval by a renewal of the original upward swelling of the site.

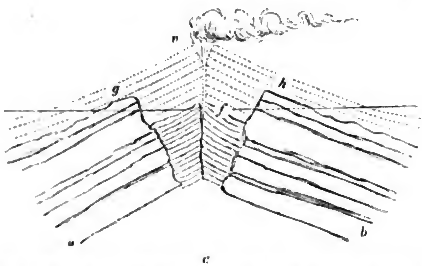

FIG. 46.—SECTION ILLUSTRATIVE OF THE ELEVATION-CRATER THEORY.

It was a matter of prime importance in the interpretation of volcanic action to have this question settled. To Poulett Scrope, Lyell, and Constant Prevost belongs the merit of disproving the Crater-elevation theory. Prevost pointed out that there was no more reason why lava should not consolidate on steep slopes than that tears or drops of wax should not do so.[1] Scrope also showed conclusively that the steep slope of the lava-beds of a volcanic cone was original.[2] Lyell, in successive editions of his works, and subsequently by an examination of the Canary Islands with Hartung, brought forward cogent arguments against the Elevation-crater theory.[3] A comparison of Fig. 46 with Fig. 47 will show at a glance the difference between this theory and the views of volcanic structure now universally accepted. The steep declivities on which lava can actually consolidate have been referred to on p. 228.

The cone grows by additions made to its surface during successive eruptions. Its angle of slope depends mainly upon the angle of repose of the erupted materials, but is apt to be modified by the effect of rain and torrents, in sweeping down the loose detritus and excavating ravines on the sides of the cone.[4]

[1] *Comptes Rendus*, i. (1835) 460; xli. (1855) p. 919. *Géol. Soc. France: Mémoires*, ii. p. 105, and *Bull.* xiv. 217. *Société Philom. Paris, Proc. Verb.* 1843, p. 13.
[2] *Considerations on Volcanoes*, 1825. *Quart. Journ. Geol. Soc.* xii. p. 326.
[3] *Phil. Trans.* 1858, p. 703.
[4] On the slopes of volcanic cones, see J. Milne, *Geol. Mag.* 1878, p. 339; 1879, p. 506.

The crater doubtless owes its generally circular form to the equal expansion in all directions of the explosive vapours from below. In some of the mud-cones already noticed the crater is not more than a few inches in diameter and depth. From this minimum every gradation of size may be met with, up to huge precipitous depressions, a mile or more in diameter, and several thousand feet in depth. In the crater of an active volcano, emitting lava and scoriæ, like Vesuvius, the walls are steep, rugged cliffs of scorched and blasted rock—red, yellow, and black. Where the material erupted is only

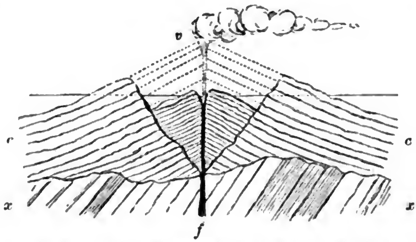

Fig. 47.—Diagram-section of a normal Volcano.

x x, Pre-volcanic platform, supposed here to consist of upraised stratified rocks, broken through by the funnel f, from which the cone of volcanic materials c c has been erupted. Inside the crater v, previously cleared by some great explosion, a minor cone may be formed during feebler phases of volcanic action, and this inner cone may increase in size until the original cone is built up again, as shown by the dotted lines.

loose dust and lapilli, the sides of the crater are slopes, like those of the outside of the cone.

The crater bottom of an active volcano of the first class forms a rough plain dotted over with hillocks or cones, from many of which steam and hot vapours are ever rising. At night the glowing lava may be seen lying in these vents, or in fissures, at a depth of only a few feet from the surface. Occasional intermittent eruptions take place and miniature cones of slag and scoriæ are thrown up. In some instances, as in the vast crater of Gurung Tengger, in Java, the crater bottom stretches out into a wide level waste of volcanic sand, driven by the wind into dunes like those of the African deserts.

A volcano commonly possesses one chief crater, often also many minor ones, of varying or of nearly equal size. The volcano of the Isle of Bourbon has three craters. Not infrequently craters appear successively, owing to the blocking up of the pipe below. Thus in the accompanying plan of the volcanic cone of the island of Volcanello (Fig. 48), one of the Lipari group, the volcanic funnel has shifted its position twice, so that three craters have successively appeared upon the cone, and partially overlap each other. It may be from this cause that some volcanic mountains are now destitute of craters, or

in other cases, because the lava has welled out in dome form without the production of scoriæ. Mount Ararat, for example, is said to have no crater; but so late as the year 1840 a fissure opened on its side whence a considerable eruption took place.

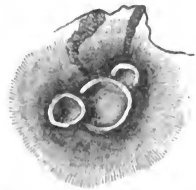

FIG. 48.—PLAN OF VOLCANELLO, SHOWING THREE SUCCESSIVE CRATERS.

Though the interior of modern volcanic cones can be at the best but very partially examined, the study of the sites of long-extinct cones laid bare after denudation shows that subsidence of the ground has commonly taken place at and round a vent. Evidence of subsidence has also been observed at some modern volcanoes (*ante* p. 232). Theoretically two causes may be assigned for this structure. In the first place the mere piling up of a huge mass of material round a given centre tends to press down the rock underneath, as some railway embankments may be observed to have done. This pressure must often amount to several hundred tons on the square foot. In the second place the expulsion of volcanic material to the surface must leave cavities underneath into which the overlying crust will naturally gravitate. These two causes combined, as suggested by Mr. Mallet, afford a probable explanation of the saucer-shaped depressions in which many ancient and some modern vents appear to lie.[1]

The following are the more important types of volcanic cones:[2]—

1. **Cones of Non-volcanic Materials.**—These are due to the discharge of steam or other aeriform product through the solid crust without the emission of any true ashes or lava. The materials ejected from the cavity are wholly, or almost wholly, parts of the surrounding rocks through which the volcanic pipe has been drilled. Some of the cones surrounding the crater-lakes (*maare*) of the Eifel consist chiefly of fragments of the underlying Devonian slates.

2. **Tuff-Cones, Cinder-Cones.**—Successive eruptions of fine dust and stones, often rendered pasty by mixture with the water so copiously condensed during an eruption, form a cone in which the materials are solidified by pressure into tuff. Cones made up only of loose cinders, like Monte Nuovo in the Bay of Baiæ, often arise on the flanks or round the roots of a great volcano, as happens to a small extent on Vesuvius, and on a larger scale upon Etna. They

[1] Mallet, *Q. J. Geol. Soc.* xxxiii. p. 740. See also the account of "Volcanic Necks," in Book IV. Part vii.

[2] Von Seebach (*Z. Deutsch. Geol. Ges.* xviii. 644) distinguished two volcanic types. 1st, *Bedded Volcanoes* (Strato-Vulkane), composed of successive sheets of lavas and tuffs, and embracing the great majority of volcanoes. 2nd, *Dome Volcanoes*, forming hills composed of homogeneous protrusions of lava, with little or no accompanying fragmentary discharges, without craters or chimneys, or at least with only minor examples of these volcanic features. He believed that the same volcano might at different periods in its history belong to one or other of these types—the determining cause being the nature of the erupted lava, which, in the case of the dome volcanoes, is less fusible and more viscid than in that of the bedded volcanoes.

likewise occur by themselves apart from any lava-producing volcano, though usually they afford indications that columns of lava have risen in their funnels, and even now and then that this lava has reached the surface.

The cones of the Eifel district have long been celebrated for their

Fig. 49.—View of the Tuff Cones of Auvergne, taken from the Top of the Cone and Crater of Puy Pariou.

wonderful perfection. Though small in size they exhibit with singular clearness many of the leading features of volcanic structure. Those of Auvergne are likewise exceedingly instructive.[1] The high plateaux of Utah are dotted with hundreds of small volcanic cinder-cones, the singular positions of which, close to the edge of profound

[1] Scrope, "Geology and Extinct Volcanoes of Central France," 2nd edit., 1858 Hibbert, "History of the Extinct Volcanoes of the Basin of Neuwied on the Lower Rhine," Edin. 1832. Von Dechen, "Geognostischer Führer zu dem Laacher See," Bonn, 1864. "Geognostischer Führer in das Siebengebirge am Rhein," Bonn, 1861.

river-gorges and on the upthrow side of faults, have already (p. 210) been noticed. Among the Carboniferous volcanic rocks of central Scotland the stumps of ancient tuff-cones, frequently with a central core of basalt, or with dykes and veins of that rock, are of common occurrence.[1]

The materials of a tuff-cone are arranged in more or less regularly stratified beds. On the outer side they dip down the slopes of the cone at the average angle of repose, which may range between 30° and 40°. From the summit of the crater lip they likewise dip inward toward the crater-bottom at similar angles of inclination (Fig. 50).

3. **Mud-cones** resemble tuff-cones in form, but are usually smaller in size and less steep. They are produced by the hardening

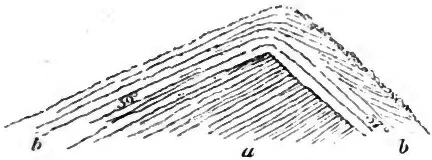

FIG. 50.—SECTION OF THE CRATER-RIM OF THE ISLAND OF VOLCANO.
a, Older tuff; *bb*, younger ashes; the crater lies to the right.

of successive outpourings of mud from the orifices already described (p. 234). In the region of the Lower Indus, where they are abundantly distributed over an area of 1000 square miles, some of them attain a height of 400 feet, with craters 30 yards across.[2]

4. **Lava-cones.**—Volcanic cones composed entirely of lava are comparatively rare, but occur in some younger tertiary and modern volcanoes. Fouqué describes the lava of 1866 at Santorin as having formed a dome-shaped elevation, flowing out quietly and rapidly without explosions. After several days, however, its emission was accompanied with copious discharges of fragmentary materials and the formation of several crateriform mouths on the top of the dome. Dome-shaped protrusions of trachyte occur in the Auvergne and Eifel districts, where their existence has been referred to the more infusible and viscid character of their component lavas, and to the absence of scoriæ and ashes.[3] Where, however, the melted rock possesses extreme liquidity, and gives rise to little or no fragmentary matter it may also build up a low cone as in the remarkable examples described by Dana from the Hawaii Islands.[4] On the summit of

[1] *Trans. Roy. Soc. Edin.* xxix. p. 455. See *postea*, Book IV. Part VII.
[2] Lyell, *Principles*, ii. p. 77.
[3] See *ante*, pp. 224, 243, *note*; also the remarks upon "Vulkanische Kuppen," *postea*, p. 256.
[4] In Wilkes's *Report of U. S. Exploring Expedition*, 1838–42.

Mauna Loa (Fig. 51), a flat lava-cone 13,760 feet above the sea, lies a crater, which in its deepest part is about 8000 feet broad, with vertical walls of stratified lava rising on one side to a height of 784 feet above the black lava-plain of the crater-bottom. From the edges of this elevated cauldron the mountain slopes outward at an angle of not more than 6°, until at a level of about 10,000 feet lower, its surface is indented by the vast pit-crater, Kilauea, about two miles long, and nearly a mile broad. So low are the surrounding slopes that these vast craters have been compared to open quarries on a hill or moor. The bottom of Kilauea is a lava-plain, dotted with lakes of extremely fluid lava in constant ebullition. The level of the lava has varied, for the walls surrounding the fiery flood consist of beds of similar lava, and are marked by ledges or platforms (Fig. 52), indicative of former successive heights of lava, as lake-terraces show former levels of water.[1] In the accompanying section

FIG. 51.—PROFILE OF LAVA DOMES OF HAWAII.

FIG. 52.—PLAN OF LAVA-CAULDRON, KILAUEA, HAWAII (DANA).

(Fig. 53) the walls rising above the lower pit (*p p'*) were found to be 342 feet high, those bounding the higher terrace (*o n n' o'*) were 650 feet high, all being composed of innumerable beds of lava, as in cliffs of stratified rocks.

FIG. 53.—SECTION OF LAVA TERRACES IN KILAUEA (DANA).

Much of the bottom of the lower lava-plain has been crusted over by the solidification of the molten rock. But large areas which shift their position from time to time remain in perpetual rapid ebullition. The glowing flood, as it boils

[1] Ellis, *Polynesian Researches.*

up with a fluidity more like that of water than what is commonly shown by molten rock, surges against the surrounding terrace walls. Large segments of the cliffs undermined by the fusion of their base, fall at intervals into the fiery waves and are soon melted.

5. **Cones of Tuff and Lava.**—This is by far the most abundant type of volcanic structure, and includes the great volcanoes of the globe. Beginning, perhaps, as mere tuff-cones, these eminences have gradually been built up by successive outpourings of lava from different sides, and by showers of dust and scoriæ. At first the lava, if the sides of the cone are strong enough to resist its pressure, may rise until it overflows from the crater. Subsequently, as the funnel becomes choked up, and the cone is shattered by repeated explosions, the lava finds egress from different fissures and openings on the cone. As the mountain increases in height, the number of lava-currents from its summit will usually decrease. Indeed, the taller a volcanic cone grows the less frequently as a rule does it erupt. The lofty volcanoes of the Andes have each seldom been more than once in eruption during a century. The peak of Teneriffe (Fig. 54) was three

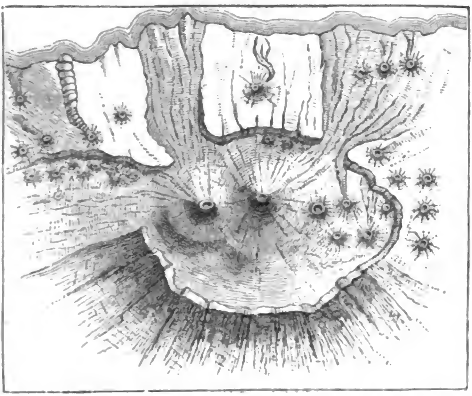

Fig. 54.—Plan of the Summit of the Peak of Teneriffe, showing the large crater and minor cones.

times active during 370 years prior to 1798. The earlier efforts of a volcano tend to increase its height, as well as its breadth; the later eruptions chiefly augment the breadth, and are often apt to diminish the height by blowing away the upper part of the cone. The formation of fissures and the consequent intrusion of a network of lava-dykes, tend to bind the framework of the volcano and strengthen it against subsequent explosions. In this way a kind of oscillation is established in the form of the cone, periods of crater eruptions being

succeeded by others when the emissions take place only laterally (*ante*, p. 214).

One consequence of lateral eruption is the formation of minor parasitic cones on the flanks of the parent volcano (p. 198). Those on Etna, more than 200 in number, are really miniature volcanoes, some of them reaching a height of 700 feet. As the lateral vents successively become extinct, the cones are buried under sheets of

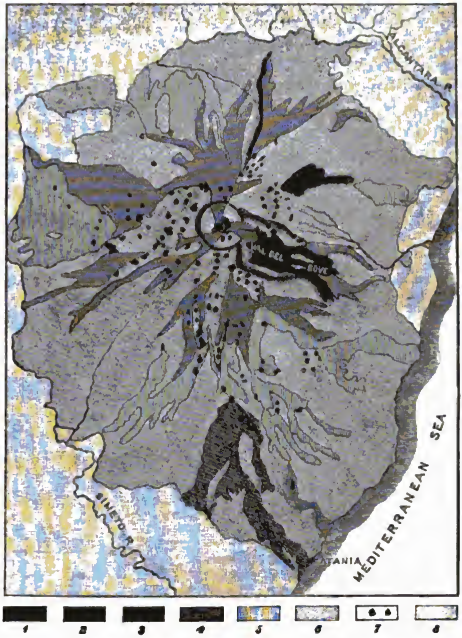

Fig. 55.—Map of Etna, after S. von Waltershausen.

1, Lava of 1879; 2, Lavas of 1865 and 1852; 3, Lava of 1669; 4, Recent Lavas; 5, Lavas of the Middle Ages; 6, Ancient Lavas of unknown date; 7, Cones and Craters; 8, Non-volcanic Rocks.

lava and showers of débris thrown out from younger openings or from the parent cone. It sometimes happens that the original funnel is disused, and that the eruptions of the volcano take place from a newer main vent. Vesuvius, for example (as shown in Fig. 56), stands on the site of a portion of the rim of the more ancient and much larger vent of Monte Somma. The pretty little example of this shifting furnished by Volcanello has been already noticed (p. 243).

While, therefore, a volcano, and more particularly one of great size, throwing out both lava and fragmentary materials, is liable to continual modification of its external form as the result of successive eruptions, its contour is likewise usually exposed to extensive alteration by the effects of ordinary atmospheric erosion as well as from the condensation of the volcanic vapours. Heavy and sudden floods produced by the rapid rainfall consequent upon a copious discharge of steam, rush down the flanks of a volcano with such volume and force as to cut deep gullies in the loose or only partially consolidated tuffs and scoriæ. Ordinary rain continues the erosion until the outer slopes, unless occasionally renewed by fresh showers of detritus, assume a curiously furrowed aspect, like a half-opened umbrella, the furrows being separated by ridges that narrow upwards towards the summit of the cone. The outer declivities of Monte Somma afford an excellent illustration of this form of surface, the numerous ravines on that side of the mountain presenting instructive sections of the prehistoric lavas and tuffs of the earlier and more important period in the history of this volcano. Similar trenches have been eroded on the southern or Vesuvian side of the original cone, but these have in great measure been filled up by the lavas of the younger mountain. The ravines in fact form natural channels for the lava, as may unfortunately be seen round the Vesuvian observatory. The building was placed on one of the ridges between two deep ravines; but the lava streams of recent years have poured into these ravines on either side and are rapidly filling them up.

FIG. 56.—SECTION OF VESUVIUS AND MONTE SOMMA FROM NORTH TO SOUTH.

a, Plain of the Campagna; *b*, Village of Somma (413 French feet); *c*, Fontana dell' Olivella (994); *d*, Casa Cancaroni (1588); *e*, Punta di Nasone (3430), on crest of old crater of Monte Somma; *f*, Atrio del Cavallo, bottom of old crater of Monte Somma; *g*, *i*, edges of modern crater (*h*) of Vesuvius (3640); *k*, Bocche Nuove (1515); *l*, Camaldoli (534); *m*, Torre dell' Annunziata, on Bay of Naples.

6. **Submarine Volcanoes.**—It is not only on the surface of the land that volcanic action shows itself. It takes place likewise under the sea, and as the geological records of the earth's past history are chiefly marine formations, the characteristics of submarine volcanic action have no small interest for the geologist. In a few instances the actual outbreak of a submarine eruption has been witnessed. Thus in the early summer of 1783 a volcanic eruption took place about thirty miles from Cape Reykjanaes

on the west coast of Iceland. An island was built up, from which fire and smoke continued to issue, but in less than a year the waves had washed the loose pumice away, leaving a submerged reef from five to thirty fathoms below sea-level. About a month after this eruption the frightful outbreak of Skaptar Jōkull already (p. 224) referred to began, the distance of this mountain from the submarine vent being nearly 200 miles.[1] Again in the year 1831, a new volcanic island (Graham's Island, Ile Julia) was thrown up, with abundant discharge of steam and showers of scoriæ, between Sicily and the coast of Africa. It reached an extreme height of 200 feet or more above the sea-level (800 feet above sea-bottom) with a circumference of 3 miles, but on the cessation of the eruptions was attacked by the waves and soon demolished, leaving only a shoal to mark its site.[2] In the year 1811 another island was formed by submarine eruption off the coast of St. Michael's in the Azores. Consisting, like the Mediterranean

Fig. 57.—Sketch of Submarine Volcanic Eruption (Sabrina Island) off St. Michael's, June, 1811.

example, of loose cinders, it rose to a height of about 300 feet with a circumference of about a mile, but subsequently disappeared.[3] In the year 1796 the island of Johanna Bogoslawa in Alaska appeared above the water and in four years had grown into a large volcanic cone, the summit of which was 3,000 feet above sea-level.[4]

Unfortunately, the phenomena of recent volcanic eruptions under

[1] Lyell, *Principles*, ii. p. 49.

[2] *Phil. Trans.* 1832. Constant Prevost, *Ann. des Sci. Nat.* xxiv. *Mém. Soc. Géol. France*, ii. p. 91.

[3] De la Beche, *Geol. Obs.* p. 70.

[4] D. Forbes, *Geol. Mag.* vii. p. 323.

the sea are for the most part inaccessible. Here and there, as among the islands of the Greek Archipelago and at Tahiti, elevation of the sea-bed has taken place, and brought to the surface beds of lava which had been erupted and had consolidated under water. It will be seen from the accompanying chart (Fig. 58), that the islands of Santorin and Therasia form the unsubmerged portions of a great crater-rim rising round a crater which descends 1278 feet below sea-level. The materials of these islands consist of a nucleus of marbles and schists nearly buried under a pile of tuffs (trass), scoriæ and

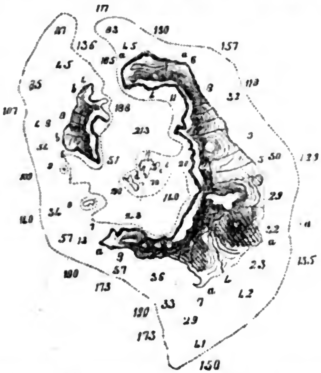

FIG. 58.—MAP OF PARTIALLY-SUBMERGED VOLCANO OF SANTORIN.
a, Thera, or Santorin; *b*, Therasia; *c*, Mikro Kaimeni; *d*, Neo Kaimeni. The figures denote soundings in fathoms, the dotted line marks the 100 fathoms line.

sheets of lava, the bedded character of which is well shown in the accompanying sketch by Admiral Spratt (Fig. 59), who with the late Professor Edward Forbes examined the geology of this interesting district in 1841. They found some of the tuffs to contain marine shells and thus to bear witness to an elevation of the sea-floor since volcanic action began. More recently the islands have been carefully studied by various observers. K. von Fritsch has found recent marine shells in many places up to heights of nearly 600 feet above the sea. The strata containing these remains he estimates to be at least 100 to 120 mètres thick, and he remarks that in every case he found them to consist essentially of volcanic débris and to rest upon volcanic rocks. It is evident therefore that these shell-bearing tuffs were originally deposited on the sea-floor after volcanic action had begun here, and that during later times they were upraised, together with the submarine lavas associated with them.[1] Fouqué concludes

[1] See Fritsch, *Z. Deutsch. Geol. Ges.* xxiii. (1871) pp. 125-213. The most complete and elaborate work is Fouqué's monograph (already cited), "Santorin et ses Eruptions," Paris, 4to, 1880, where copious analyses of rocks, minerals, and gaseous emanations, with maps and numerous admirable views and sections, are given. In this volume a bibliography of the locality will be found.

Fig. 59.—View of the Interior of the Crater of Santorin from the Entrance.

a, Town of Apanomeria, standing on tuffs, &c.; *b*, North-west cape of Santorin, with bedded tuffs and lavas; *c*, Mount St. Elias (568 mètres), consisting of marble (shown by oblique lines in the chart, Fig. 58) and forming with the surrounding district a non-volcanic tract in the midst of the lavas and tuffs; *d*, Mikro Kaimeni; *e*, Neo Kaimeni, the scene of the eruptions in 1866–67; *f*, Therasia, an island composed, like Santorin, of beds of tuff, slags, and lavas.

that the volcano formed at one time a large island with wooded slopes, and a somewhat civilized human population, cultivating a fertile valley in the south-western district, and that in pre-historic times the tremendous explosion occurred whereby the centre of the island was blown out.

The similarity of the structure of Santorin to that of Somma is obvious. Volcanic action still continues there, though on a diminished scale. In 1866–67 an eruption took place on Neo Kaimeni, one of the later-formed islets in the centre of the old crater, and greatly added to its area and height.

The recent eruptions of Santorin, which have been studied in great detail, are specially interesting from the additional information they have supplied as to the nature of volcanic vapours and gases. Among these, as already stated (p. 201), free hydrogen plays an important part, constituting at the focus of discharge thirty per cent. of the whole. By their eruption under water the mingling of these gases with atmospheric air and the combustion of the inflammable compounds is there prevented, so that the gaseous discharges can be collected and analysed. Probably were operations of this kind more practicable at terrestrial volcanoes free hydrogen and its compounds would be more abundantly detected than has hitherto been possible.

The numerous volcanoes which dot the Pacific Ocean,[1] probably in most cases began their career as submarine vents, their eventual appearance as subaerial cones being due to the accumulation of erupted material, and perhaps, also, as in the case of Santorin, to actual upheaval of the sea-bottom. The lonely island of St. Paul[2] (Fig. 60), lying in the Indian Ocean more than 2000 miles from the nearest land, is a notable example of the summit of a volcanic mountain rising to the sea-level in mid-ocean. Its circular crater, broken down on the north-east side, is filled with water, having a depth of 30 fathoms.

Recent observations by Von Drasche have shown that at Réunion, during the early submarine eruptions of that volcano coarsely crystalline rocks (gabbro) were emitted, that these were succeeded by andesitic and trachytic lavas: but that when the vent rose above the sea basalts were poured out.[3] It is interesting to find that the order of appearance of the lavas in a submarine volcano so closely resembles

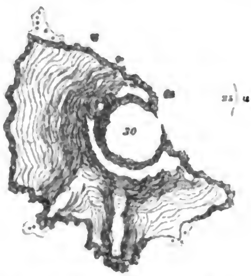

FIG. 60.—VOLCANIC CRATER OF ST. PAUL ISLAND, INDIAN OCEAN.

that generally noticed in terrestrial volcanic districts. Fouqué observes that at Santorin some of the early submarine lavas are identical with those of later subaerial origin, but that the greater part of them belong to an entirely different series, being acid rocks, belonging to the group of hornblende-andesites, while the subaerial rocks are augite-andesites. The acidity of these lavas has been largely increased by the infusion into them of much silica, chiefly in the form of opal. They differ much in aspect, being sometimes compact, scoriaceous, hard like millstone, with perlitic and spherulitic structures, while they frequently present the characters of trass impregnated with opal and zeolites. Among the fragmental ejections there occur blocks of schist and granitoid rocks, probably representing the materials below the sea-floor through which the first

[1] See Darwin's "Volcanic Islands," 2nd edit., 1876.
[2] See *Assoc. Française*, iv. p. 581.
[3] Tschermak's *Mineralogische Mittheil.* 1876, pp. 42, 157, give an interesting account of the Philippine volcanoes. A similar structure occurs at Palma. Cohen. *Neues Jahrb.* 1879, p. 482.

explosion took place (p. 206). During the eruption of 1866, some islets of lava rose above the sea in the middle of the bay, near the active vent. The rock in these cases was compact, vitreous, and much cracked.[1]

Fig. 61.—View of the Peak of Teneriffe and Coast Erosion.

Among submarine volcanic formations the tuffs differ from those laid down on land chiefly in their organic contents; but partly also in their more distinct and originally less inclined bedding and in their tendency to the admixture of non-volcanic or ordinary mechanical sediment with the volcanic dust and stones. No appreciable difference either in external aspect or in internal structure seems yet to have been established between subaerial and submarine lavas. Some undoubtedly submarine lavas are highly scoriaceous. There is no reason indeed why slaggy lava and loose, non-buoyant scoriæ should not accumulate under the pressure of a deep column of the ocean. At the Hawaii Islands, on 25th February 1877, masses of pumice, during a submarine volcanic explosion, were ejected to the surface, one of which struck the bottom of a boat with considerable violence and then floated. When we reflect, indeed, to what a considerable extent the bottom of the great ocean basins is dotted over with volcanic cones, rising often solitary from profound depths, we can believe that a large proportion of the actual eruptions in oceanic areas may take place under the sea. The immense abundance and wide diffusion of volcanic detritus over the bottom of the Pacific and Atlantic oceans, even at distances remote from land, as made known by the voyage of the "Challenger," doubtless indicate the prevalence and persistence of submarine volcanic action, even though, at the same time, an extensive diffusion of volcanic débris from the islands is admitted to be effected by winds and ocean-currents.

[1] Fouqué, *Op. cit.*

Volcanic islands, unless continually augmented by renewed eruptions, are attacked by the waves and cut down. The examples of Graham's Island and Sabrina above cited show how rapid this

FIG. 62. VIEW OF ST. PAUL ISLAND, INDIAN OCEAN, FROM THE EAST (CAPT. BLACKWOOD IN ADMIRALTY CHART).

a, Nine-pin Rock, a stack of harder rock left by the sea; *b*, entrance to crater lagoon (see Fig. 60); *c*, *d*, *e*, cliffs composed of bedded volcanic materials dipping towards the south, and much eroded at the higher end (*c*) by waves and subaerial waste; *f*, southern point of the island, likewise cut away into a cliff.

disappearance may be. The Island of Volcano has the base of its slopes truncated by a line of cliff due to marine erosion. The island of Teneriffe shows in the same way that the sea is cutting back the land towards the great cone (Fig. 61). The island of St. Paul (Figs. 60, 62) brings before us in a more impressive way the tendency of volcanic islands to be destroyed unless replenished by continual additions to their surface. At St. Helena lofty cliffs of volcanic rocks 1000 to 2000 feet high bear witness to the enormous denudation whereby masses of basalt two or three miles long, one or two miles broad, and 1000 to 2000 feet thick, have been entirely removed.[1]

ii. *Fissure (Massive) Eruptions.*

Under the head of massive or homogeneous volcanoes some geologists have included a great number of bosses or dome-like projections of once-melted rock which, in regions of extinct volcanoes, rise conspicuously above the surface without any visible trace of cones or craters of fragmentary material. They are usually regarded as protrusions of lava, which, like the Puy de Dôme in Auvergne, assumed a dome-form at the surface without spreading out in sheets over the surrounding country, and with no accompanying fragmentary discharges. But the mere absence of ashes and scoriæ is no proof that these did not once exist, or that the present knob or boss of lava may not originally have solidified within a cone of tuff which has been subsequently removed in denudation. The extent to which the surface of the ground has been changed by ordinary atmospheric waste, and the comparative ease with which loose volcanic dust and cinders might have been entirely removed require to be considered. Hence, though the ordinary explanation is no doubt in some cases correct, it may be doubted whether a large proportion of the examples cited from the Rhine, Bohemia, Hungary,

[1] Darwin, "Volcanic Islands," p. 104.

and other regions, ought not rather to be regarded as the remaining roots of true volcanic cones, like the "necks" so abundant in the ancient volcanic districts of Britain (Book IV. Part VII.). If the tuff of a cone up the funnel of which lava rose and solidified were swept away, we should find a central lava plug or core resembling the volcanic "heads" (*vulkanische Kuppen*) of Germany. Unquestionably, lava has in innumerable instances risen in this way within cones of tuff or cinders, partially filling them without flowing out into the surrounding country.[1]

But while, on either explanation of their origin, these volcanic "heads" find their analogues in the emissions of lava in modern volcanoes, there are numerous cases in old volcanic areas where the eruptions, so far as can now be judged, were not attended with the production of any dome, cone or crater. In former geological ages, and perhaps even in the existing period, extensive eruptions of lava without the accompaniment of scoriæ or with hardly any fragmentary materials, have taken place over wide areas from scattered vents, but more usually it would seem from lines or systems of fissures. Vast sheets of lava have in this manner been poured out to a depth of many hundred feet, completely burying the previous surface of the land and forming wide plains or plateaux. These truly "massive eruptions" have been held by Richthofen[2] and others to represent the grand fundamental character of vulcanism, modern volcanic cones being regarded merely as parasitic excrescences on the subterranean lava-reservoirs, very much in the relation of minor cinder cones to their parent volcano.[3]

Though a description of these old fissure- or massive-eruptions ought properly to be included in Book IV., the subject is so closely connected with the dynamics of existing active volcanoes that an account of the subject may be given here. Some of the most remarkable examples of this type of volcanic structure occur in western North America. Among these that of the Snake River plain in Idaho may be briefly described (Fig. 63). Surrounded on the north and east by lofty mountains, it stretches westward as an apparently boundless desert of sand and bare sheets of black basalt. A few streams descending into the plain from the hills are soon swallowed up and lost. The Snake River, however, flows across it and has cut out of its lava-beds a series of picturesque gorges and rapids. The extent of country which has been flooded with basalt in this and adjoining regions of Oregon and Washington has not yet been accurately surveyed, but has been estimated to cover a larger area than France and Great Britain combined. Looked at from any point on its surface, one of these lava-plains appears as a vast level surface like that of a lake-bottom. This uniformity has been

[1] Von Seebach, *Z. Deutsch. Geol. Ges.* xviii. p. 643. F. von Hochstetter, *Neues Jahrb.* 1871, p. 469. Reyer, *Jahrb. K. K. Geol. Reichsanstalt*, 1878, p. 81; 1879, p. 463.
[2] *Trans. Acad. Sci. California*, 1868.
[3] *Proc. Roy. Phys. Soc. Edin.* v. 236. *Nature*, xxiii. p. 3.

produced either by the lava rolling over a plain or lake-bottom, or by the complete effacement of an original undulating contour of the ground under hundreds of feet of lava in successive sheets. The lava rolling up to the base of the mountains has followed the sinuosities of their margin, as the waters of a lake follow its promontories and bays. The author crossed the Snake River plain in 1879, and likewise rode for many miles along its northern edge. He found the surface to be everywhere marked with low hummocks or ridges of bare black basalt, the surfaces of which

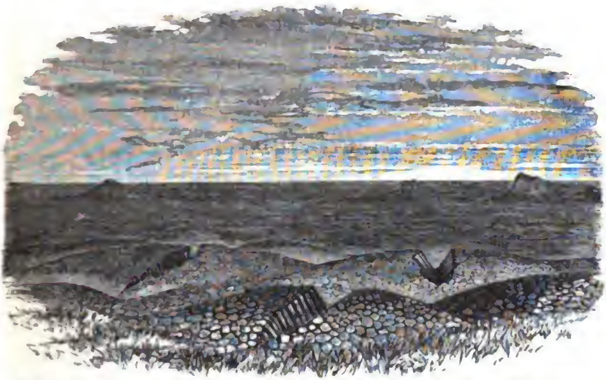

FIG. 63.—VIEW OF THE GREAT BASALT PLAIN OF THE SNAKE RIVER, IDAHO, WITH RECENT CONES.

exhibited a reticulated pavement of the ends of columns. In some places, there was a perceptible tendency in these ridges to range themselves in one general north-easterly direction, when they might be likened to a series of long, low waves or ground-swells. In many instances the crest of each ridge had cracked open into a long fissure which presented along its walls a series of tolerably symmetrical columns (Fig. 63). That these ridges were original undulations of the lava, and had not been produced by erosion was indicated by the fact that the columns were perpendicular to them and changed in direction according to the form of the ground which was the original cooling surface of the lava. Though the basalt was sometimes vesicular, no layers of slag or scoriæ were anywhere observed, nor did the surfaces of the ridges exhibit any specially scoriform character.

There are no visible cones whence this enormous flood of basalt could have flowed. It probably escaped from many fissures still concealed under the sheets which issued from them. That it was not the result of one sudden outpouring of rock is shown by the

distinct bedding along the Snake River ravines. It arose from what may have been on the whole a continuous though locally intermittent welling out of lava, probably from many fissures extending over a wide tract of Western America during a late Tertiary period, if, indeed, the eruptions did not partly come within the time of the human occupation of the continent.

At a few points on the plain and on its northern margin the author observed some small cinder cones (Fig. 63). These were evidently formed during the closing stages of volcanic action, and may be compared to the minor cones on a modern volcano, or better, to those on the surface of a recent lava-stream.

In Europe during Miocene times similar enormous outpourings of basalt covered many hundreds of square miles. The most important of these is that which occupies a large part of the north-east of Ireland, and in disconnected areas extends through the Inner Hebrides and the Faröe Islands into Iceland. Throughout that region the paucity of evidence of volcanic vents is truly remarkable. So extensive has been the denudation that the inner structure of the volcanic plateaux has been admirably revealed. The ground beneath and around the basalt sheets has been rent into innumerable fissures which have been filled by the rise of basalt into them. A vast number of basalt-dykes ranges from the volcanic area eastwards across Scotland and the north of England. Towards the west the molten rock reached the surface and was poured out there, while to the eastward it does not appear to have overflowed, or at least, all evidence of the out-flow has been removed in denudation. When we reflect that this system of dykes can be traced from the Orkney Islands southwards into Yorkshire and across Britain from sea to sea, over a total area of probably not less than 100,000 square miles, we can in some measure appreciate the volume of molten basalt which in Miocene times underlay large tracts of the site of the British Islands, rose up in so many thousands of fissures, and poured forth at the surface over so wide an area in the north-west.

In Africa vast basaltic plateaux occur in Abyssinia, where by the denuding effect of heavy rains they have been carved into picturesque hills, valleys, and ravines.[1] In India an area of at least 200,000 square miles is covered by the singularly horizontal volcanic plateaux of the "Deccan Traps" (lavas and tuffs), which belong to the Cretaceous period and attain a thickness of 6000 feet or more.[2] The underlying platform of older rock, where it emerges from beneath the edges of the basalt tableland, is found to be in many places traversed by dykes; but no cones and craters are anywhere visible. In these, and probably in many other examples still undescribed, the formation of great plains or plateaux of level sheets of lava is to be explained by "fissure-eruptions" rather than by the operations of volcanoes of the familiar "cone and crater" type.

[1] Blanford's *Abyssinia*, 1870, p. 181.
[2] *Geology of India*, Medlicott and Blanford, p. 299.

§. 4. Geographical and geological distribution of volcanoes.

Adequately to trace the distribution of volcanic action over the globe account ought to be taken of dormant and extinct volcanoes, likewise of the proofs of volcanic outbreaks during earlier geological periods. When this is done we learn on the one hand that innumerable districts have been the scene of prolonged volcanic activity, where there is now no token of underground commotion, and on the other that volcanic outbursts have been apt to take place again and again after wide intervals on the same ground, some modern active volcanoes being thus the descendants and representatives of older ones. Some of the facts regarding former volcanic action have been already stated. Others will be given in Book IV. Part VII.

Confining attention to vents now active, the chief facts regarding their distribution over the globe may be thus summarised. (1.) Volcanoes occur along the margins of the ocean basins, particularly along lines of dominant mountain ranges, which either form part of the mainland of the continents or extend as adjacent lines of islands. The vast hollow of the Pacific is girdled with a wide ring of volcanic foci. (2.) Volcanoes rise as a striking feature in the heart of the ocean basins. Most of the oceanic islands are volcanic. The scattered coral islands have in all likelihood been built upon the tops of submarine volcanic cones. (3.) Volcanoes are situated, as a rule, close to the sea. When they occur inland they sometimes appear in the neighbourhood of a lake. Yet as instances have been observed where volcanoes have appeared at great distances from any sheet of water, the proximity of a lake or of the sea cannot be regarded as always necessary for the evolution of volcanic phenomena. (4.) The dominant arrangement of volcanoes is in series along subterranean lines of weakness, as in the chain of the Andes, the Aleutian Islands, and the Malay Archipelago. A remarkable zone of volcanic vents girdles the globe from Central America eastward by the Azores and Canary Islands to the Mediterranean, thence to the Red Sea, and through the chains of islands from the south of Asia to New Zealand and the heart of the Pacific. (5.) On a smaller scale the linear arrangement gives place to one in groups, as in Italy, Iceland, and the volcanic islands of the great oceans.

Besides the existence of what are called extinct volcanoes, the geologist can adduce proofs of the former presence of active volcanoes in many countries where cones, craters and all the ordinary aspects of volcanic mountains, have long disappeared. Sheets of lava, beds of tuff, dykes, and necks representing the sites of volcanic vents have been recognized abundantly (Book IV. Part VII.). These manifestations of volcanic action, moreover, have as wide a range in geological time as they have in geographical area. Every great

geological period, back at least as far as the Lower Silurian, has had its volcanoes.[1] In Britain, for instance, there were active volcanic vents in the Lower Silurian period, whence the lavas and tuffs of Snowdon, Aran Mowddwy, and Cader Idris were ejected. The Lower Old Red Sandstone epoch was one of prolonged activity in central Scotland. The earlier half of the Carboniferous period likewise witnessed the outburst of innumerable small volcanoes over the same region. During Permian time a few scattered vents existed in the south-west of Scotland, and in the epoch of the New Red Sandstone some similar points of eruption appeared in the south of England. The older Tertiary ages were distinguished by the outpouring of the enormous basaltic plateaux of Antrim and the Inner Hebrides.

In France and Germany likewise palæozoic time was marked by the eruption of many diabase and porphyrite lavas, followed in the Permian epoch by a great outburst of porphyries, while on the other hand the late Tertiary volcanoes of Auvergne, the Eifel, Bohemia and Hungary belong almost to the existing period. Recent research has brought to light evidence of a long succession of Tertiary and post-tertiary volcanic outbursts in Western America (Nevada, Oregon, Idaho, Utah, &c.). Contemporaneous volcanic rocks are associated with Palæozoic, Secondary and Tertiary formations in New Zealand, and volcanic action there is not yet extinct.

Thus it can be shown that, within the same comparatively limited geographical space, volcanic action has been rife at intervals during a long succession of geological ages. Even round the sites of still active vents traces of far older eruptions may be detected, as in the case of the existing active volcanoes of Iceland which rise from amid Tertiary lavas and tuffs. Volcanic action, which now manifests itself so conspicuously along certain lines, seems to have continued in that linear development for protracted periods of time. The actual vents have changed, dying in one place and breaking out in another, yet keeping on the whole along the same tracts.

§ 5. Causes of Volcanic Action.

The *modus operandi* whereby the internal heat of the globe manifests itself in volcanic action is a problem to which as yet no satisfactory solution has been found. Were this action merely an expression of the intensity of the heat, we might expect it to have manifested itself in a far more powerful manner in former periods, and to exhibit a regularity and continuity commensurate with the exceedingly slow diminution of the earth's temperature. But there is no geological evidence in favour of greater volcanic intensity in ancient than in more recent periods; on the contrary, it may be

[1] The existence of pre-Cambrian lavas has been cited from several parts of England and Wales (see the section on Archæan Rocks in Book vi.).

doubted whether any of the Palæozoic volcanoes equalled in magnitude those of Tertiary and perhaps even post-tertiary times. On the other hand, no feature of volcanic action is more conspicuous than its spasmodic fitfulness.

As physical considerations negative the idea of a comparatively thin crust surmounting a molten interior whence volcanic energy might be derived (*ante*, p. 49), geologists have found themselves involved in great perplexity to explain volcanic phenomena, for the production of which a source of no great depth would seem to be necessary. They have supposed the existence of pools or lakes of liquid lava lying beneath the crust, and at an inconsiderable depth from the surface. Some have appealed to the influence of the contraction of the earth's mass, erroneously assuming the contraction to be now greater in the outer than in the inner portions, and that the effect of this external contraction must be to squeeze out some of the internal molten matter through weak parts of the crust. Cordier, for example, calculated that a contraction of only a single millimetre (about $\frac{1}{25}$th of an inch) would suffice to force out to the surface lava enough for 500 eruptions, allowing 1 cubic kilometre (about 1300 million cubic yards) for each eruption.

That volcanic action is one of the results of terrestrial contraction can hardly be doubted, though we are still without satisfactory data as to the connection between the cause and the effect. It will be observed that volcanoes occur chiefly in lines along the crests of terrestrial ridges. There is evidently therefore a connection between the elevation of these ridges and the extravasation of molten rock at the surface. The formation of continents and mountain chains has already been referred to as probably consequent on the subsidence and readjustment of the cool outer shell of the planet upon the hotter and more rapidly contracting nucleus. Every such movement, by relieving pressure on regions below the axis of elevation, will tend to bring up molten rock nearer the surface, and thus to promote the formation and continued activity of volcanoes.

The fissure eruptions wherein lava has risen through innumerable rents in the ground across the whole breadth of a country, and has been poured out at the surface over areas of many thousand square miles, flooding them sometimes to a depth of several thousand feet, undoubtedly prove that molten rock existed at some depth over a large extent of territory, and that by some means still unknown, it was forced out to the surface (*ante* p. 255). In investigating this subject it would be important to discover whether any evidence of great terrestrial crumpling or other movement of the crust can be ascertained to have taken place about the same geological period as a stupendous outpouring of lava—whether, for example, the great lava fields of Idaho may have had any connection with contemporaneous flexure of the North American mountain system, or whether the basalt plateaux of Antrim, Scotland, Faröe and Iceland may possibly have been in their origin sympathetic with

the Miocene upheaval of the Alps and other middle Tertiary movements in Europe.

But in the ordinary phase of volcanic action, marked by the copious evolution of steam and the abundant production of dust, slags and cinders, from one or more local vents, it is manifest that one main cause of volcanic excitement is the expansive force exerted by vapours present in the molten magma from which lavas proceed.[1] Whether and to what extent these vapours are parts of the aboriginal constitution of the earth's interior, or are derived by descent from the surface, is still an unsolved problem. So large a proportion being steam, much of the superheated vapours of volcanic vents may have been supplied by the descent of water from above ground. The floor of the sea and the beds of rivers and lakes are all leaky. Rain sinking beneath the surface of the land, percolates down cracks and joints, and infiltrates through the very pores of the rocks. The presence of nitrogen among the gaseous discharges of volcanoes indicates no doubt the decomposition of water containing atmospheric gases. The abundant volcanic sublimations of chlorides are such as might probably result from the decomposition of sea water.

Accordingly, there has arisen a prevalent belief among geologists, that it is to the enormous expansive force of perhaps white-hot water imprisoned in the molten magma at the roots of volcanoes that the explosions of a crater and the subsequent rise of a lava-column are due. It has been supposed that, somewhat like the reservoirs in which hot water and steam accumulate under geysers, reservoirs of molten rock receive a constant influx of water from the surface, which cannot escape by other channels, but is absorbed by the internal magma at an enormously high temperature and under vast pressure. In the course of time the materials filling up the chimney are unable to withstand the upward expansion of this imprisoned vapour and water, so that, after some premonitory rumblings, the whole opposing mass is blown out, and the vapour escapes in the well-known masses of cloud. Meanwhile, the removal of the overlying column relieves the pressure on the lava underneath, saturated with vapours or superheated water. This lava therefore begins to rise in the funnel until it forces its way through some weak part of the cone, or pours over the top of the crater. After a time, the vapour being expended, the energy of the volcano ceases, and there comes a variable period of repose, until a renewal of the same phenomena brings on another eruption. By such successive paroxysms it is supposed that the forms of the internal reservoirs and tunnels are changed; new spaces for the accumulation of superheated water are opened, whence in time fresh volcanic vents issue, while the old ones gradually die out.

An obvious objection to this explanation is the difficulty of conceiving that water should descend at all against the expansive

[1] See Reyer's *Beitrag zur Physik der Eruptionen*, Vienna, 1877, where the part taken by absorbed gases and vapours is cogently advocated.

force within. But Daubrée's experiments have shown that, owing to capillarity, water may permeate rocks against a high counter-pressure of steam on the further side, and that so long as the water is supplied, whether by minute fissures or through pores of the rocks, it may, under pressure of its own superincumbent column, make its way into highly heated regions.[1] Experience in deep mines, however, rather goes to show that the permeation of water through the pores of rocks gets feebler as we descend.

Reference may be made here to a theory of volcanic action in which the influence of terrestrial contraction as the grand source of volcanic energy has recently been insisted upon by Mr. Mallet.[2] He maintains that all the present manifestations of hypogene action are due directly to the more rapid contraction of the hotter internal mass of the earth and the consequent crushing in of the outer cooler shell. He points to the admitted difficulties in the way of connecting volcanic phenomena with the existence of internal lakes of liquid matter, or of a central ocean of molten rock. Observations made by him, on the effects of the earthquake shocks accompanying the volcanic eruptions of Vesuvius and of Etna, showed that the focus of disturbance could not be more than a few miles deep; that, in relation to the general mass of the globe, it was quite superficial, and could not possibly have lain under a crust of 800 miles or upwards in thickness. The occurrence of volcanoes in lines, and especially along some of the great mountain-chains of the planet, is likewise dwelt upon by him as a fact not satisfactorily explicable on any previous hypothesis of volcanic energy. But he contends that all these difficulties disappear when once the simple idea of cooling and contraction is adequately realized. "The secular cooling of the globe," he remarks, "is always going on, though in a very slowly descending ratio. Contraction is therefore constantly providing a store of energy to be expended in crushing parts of the crust, and through that providing for the volcanic heat. But the crushing itself does not take place with uniformity; it necessarily acts *per saltum* after accumulated pressure has reached the necessary amount at a given point, where some of the pressed mass, unequally pressed as we must assume it, gives way, and is succeeded perhaps by a time of repose, or by the transfer of the crushing action elsewhere to some weaker point. Hence, though the magazine of volcanic energy is being constantly and steadily replenished by secular cooling, the effects are intermittent." He offers an experimental proof of the sufficiency of the store of heat produced by this internal crushing to cause all the phenomena of existing volcanoes.[3] The slight compar-

[1] Daubrée, *Géologie Expérimentale*, p. 274. See also Tschermak, *Sitzber. Akad. Wien* March 1877. Reyer, *Beitrag zur Physik der Eruptionen*, § I.

[2] *Phil. Trans.*, 1873. See also Daubrée's experimental determination of the quantity of heat evolved by the internal crushing of rocks. *Géologie Expérimentale*, p. 448.

[3] The elaborate and careful experimental researches of this observer will reward attentive perusal. Mallet estimates from experiment the amount of heat given out by the crushing of different rocks (syenite, granite, sandstone, slate, limestone), and con-

ative depth of the volcanic foci, their linear arrangement, and their occurrence along lines of dominant elevation become, he contends, intelligible under this hypothesis. For since the crushing in of the crust may occur at any depth, the volcanic sources may vary in depth indefinitely; and as the crushing will take place chiefly along lines of weakness in the crust, it is precisely in such lines that crumpled mountain-ridges and volcanic funnels should appear. Moreover, by this explanation its author seeks to harmonize the discordant observations regarding variations in the rate of increase of temperature downward within the earth, which have already been cited and referred to unequal conductivity in the crust (p. 47). He points out that in some parts of the crust the crushing must be much greater than in other parts; and since the heat "is directly proportionate to the local tangential pressure which produces the crushing and the resistance thereto," it may vary indefinitely up to actual fusion. So long as the crushed rock remains out of reach of a sufficient access of subterranean water, there would, of course, be no disturbance. But if, through the weaker parts, water enough should descend and be absorbed by the intensely hot crushed mass, it would be raised to a very high temperature, and, on sufficient diminution of pressure, would flash into steam and produce the commotion of a volcanic eruption.

This ingenious theory requires the operation of sudden and violent movements, or at least that the heat generated by the crushing should be more than can be immediately conducted away through the crust. Were the crushing slow and equable, the heat developed by it might be so tranquilly dissipated that the temperature of the crust might not be sensibly affected in the process, or not to such an extent as to cause any appreciable molecular rearrangement of the particles of the rock. But an amount of internal crushing insufficient to generate volcanic action may have been accompanied by such an elevation of temperature as to induce important changes in the structure of rocks.

There is, indeed, strong evidence that, among the consequences arising from the secular contraction of the globe, masses of sedimentary strata, many thousands of feet in thickness, have been crumpled and crushed, and that the crumpling has often been accompanied by such an amount of heat and evolution of chemical activity as to produce an interchange and rearrangement of the elements of the rocks,—this change sometimes advancing to the point of actual fusion. (See *postea* p. 308, and Book IV. Part VIII.) There is reason to believe that some at least of these periods of intense terrestrial disturbance have been followed by periods of prolonged volcanic action in the disturbed areas. Mr. Mallet's theory is thus, to some extent,

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cludes that a cubic mile of the crust taken at the mean density would, if crushed into powder, give out heat enough to melt nearly 3½ cubic miles of similar rock, assuming the melting point to be 2000° Fahr.

supported by independent geological testimony. The existence, however, of large reservoirs of fused rock, at a comparatively small depth beneath the surface, may be conceived as probable, apart from the effects of crushing. The connection of volcanoes with lines of elevation, and consequent weakness in the earth's crust, is precisely what might have been anticipated on the view that the nucleus, though practically solid, is at such a temperature and pressure that any diminution of the pressure, by corrugation of the crust or otherwise, will cause the subjacent portion of the nucleus to melt. Along lines of elevation the pressure is relieved, and consequent melting may take place. On these lines of weakness and fracture, therefore, the conditions for volcanic excitement may be conceived to be best developed. Water, able soonest to reach there the intensely heated materials underneath the crust, may give rise to volcanic explosions. The periodicity of eruptions may thus depend upon the length of time required for the storing up of sufficient steam, and on the amount of resistance in the crust to be overcome. In some volcanoes the intervals of activity, like those of many geysers, return with considerable regularity. In other cases, the shattering of the crust, or the upwelling of vast masses of lava, or the closing of subterranean passages for the descending water, or other causes may vary the conditions so much, from time to time, that the eruptions follow each other at very unequal periods, and with very discrepant energy. Each great outburst exhausts for a while the vigour of the volcano, and an interval is needed for the renewed accumulation of vapour.

But beside the mechanism by which volcanic eruptions are produced, a further problem is presented by the varieties of materials ejected and the differences which these exhibit at neighbouring vents, and even sometimes at successive eruptions from the same vent. It is common to find that the earlier lavas of a volcano have been acid (trachytes, liparites, obsidians, &c.), while the later are basic (andesites, basalts, &c.). Richthofen has deduced from observations in Europe and North America a general order of volcanic succession which has been well sustained by subsequent investigation. He states that volcanic rocks may be arranged in five great groups, and that all over the world these groups have appeared in the following sequence. 1. Propylite; 2. Andesite; 3. Trachyte; 4. Rhyolite; 5. Basalt.[1] The sequence is seldom or never complete in any one locality; sometimes only one member of the series may be found, but when two or more occur they take, it is affirmed, this order, basalt being everywhere the latest of the series. Instances have been noticed of apparent or real exceptions to Richthofen's law. But the continued study of the great volcanic plateaux of Western America has supplied many new examples of its wide application.[2]

[1] "The Natural System of Volcanic Rocks." F. Richthofen. *California Acad. Sci.* 1868.

[2] See in particular Captain Dutton's valuable *Report on the Geology of the High Plateaux of Utah*, Washington, 1880, p. 64.

Reference has already (p. 58) been made to the speculation of Durocher as to the existence within the crust of an upper siliceous layer with a mean of 71 per cent. of silica and a lower basic layer with about 51 per cent. of silica. Bunsen also came to the conclusion that volcanic rocks are mixtures of two original normal magmas —the normal trachytic (with 67—76 silica, and a ratio of acid to base of 5 to 1), and the normal pyroxenic (with 47—48 silica and a ratio of 3 to 2 between acid and base). The varying proportions in which these two original extreme magmas have been combined are, in Bunsen's view, the cause of the differences of volcanic rocks. We may conceive these two layers to be superposed upon each other, according to relative densities, and the composition of the last erupted at the surface to depend upon the depth from which it has been derived.[1] The earlier explosions of a volcano may be supposed to take place usually from the upper lighter and more siliceous layer, and the lavas ejected should be consequently acid, as in fact they are, while the later eruptions, reaching down to deeper and heavier zones of the magma, would bring up such basic lavas as basalt. Certainly the general similarity of the volcanic rocks all over the globe would appear to prove that there must be considerable uniformity of composition in the zones of intensely hot material from which volcanic rocks are derived, and the general order of succession in the appearance of lavas, shows that some arrangement in relation to density probably exists within the crust.[2]

Many difficulties, however, remain yet to be explained before our knowledge of volcanic action can be regarded as more than rudimentary. For example why should two adjoining vents, like Mauna Loa and Kilauea, have their lava column at such widely different levels as to show that there can be no real connection between them? Why should two neighbouring vents sometimes eject, the one acid, the other basic lavas? Why should even the same vent occasionally exhibit an alternation of acid and basic eruptions? To these and other questions in the mechanism of volcanoes no satisfactory answers have yet been given. In Book IV., Part VII., a description is given of the part volcanic rocks have played in building up what we see of the earth's crust, and the student will there find other illustrations of facts and deductions which have been given in the previous pages.

Section II.—Earthquakes.[3]

The term Earthquake denotes any natural subterranean concussion, varying from such slight tremors as to be hardly perceptible

[1] See S. von Waltershausen, *Sicilien und Island*, p. 416. Reyer, *Beitrag zur Physik der Eruptionen*, iii.

[2] In the memoir by Captain Dutton, cited in a previous note, the hypothesis is maintained that the order of appearance of the lavas is determined by their relative density and fusibility, the most basic and heaviest, though most easily fused, requiring the highest temperature to diminish their density to such an extent as to permit them to be erupted.

[3] On the phenomena of earthquakes consult Mallet, *Brit. Assoc.* 1847, part ii. p. 30;

up to severe shocks, by which houses are levelled, rocks dislocated, landslips precipitated, and many human lives destroyed. The phenomena are analogous to the shock communicated to the ground by explosions of mines or powder-works. They may be most intelligibly considered as wave-like undulations propagated through the solid crust of the earth. In Mr. Mallet's language an earthquake may be defined as "the transit of a wave of elastic compression, or of a succession of these, in parallel or intersecting lines through the solid substance and surface of the disturbed country." The passage of this wave of shock constitutes the real earthquake.

Besides the wave of shock transmitted through the solid crust, waves are also propagated through the air, and, where the site of the impulse is not too remote, through the ocean. Earthquakes originating under the sea, but not far from land, are sometimes specially destructive in their effects. They illustrate well the three kinds of waves associated with the progress of an earthquake. These are, 1st, The true earth-wave through the earth's crust; 2nd, a wave propagated through the air to which the characteristic sounds of rolling waggons, distant thunder, bellowing oxen, &c., are due; 3rd, Two sea-waves, one of which travels on the back of the earth-wave and reaches the land with it, producing no sensible effect on shore; the other an enormous low swell, caused by the first sudden blow of the earth-wave, but travelling at a much slower rate, and reaching land often several hours after the earthquake has arrived.

Velocity.—Experiments have been made to determine the velocity of the earth-wave, and its variation with the nature of the material through which it is propagated. Mr. Mallet found that the shock produced by the explosion of gunpowder at Holyhead travelled at the rate per second of 951 feet in wet sand, 1283 feet in friable granite, and 1640 feet in solid granite. Observations of the time at which an earthquake has successively visited the different places on its track have shown similar variations in the rate of movement. Thus in the Calabrian earthquake of 1857, the wave of shock varied from 658 to 989 feet per second, the mean rate being 789 feet. The earthquake at Viège in 1855 was estimated to have travelled northwards towards Strasburg at a rate of 2861 feet per second, and southwards towards Turin at a rate of 1398 feet, or less than half the northern speed. The rate of the central European earthquake of

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1850, p. 1; 1851, p. 272; 1852, p. 1; 1858, p. 1; 1861, p. 201. "The Great Neapolitan Earthquake of 1857," 2 vols., 1862. D. Milne, *Edin. New Phil. Journ.* xxxi.-xxxvi. A. Perrey, *Mém. Couronn. Bruxelles*, xviii. (1844) *Comptes rendus*, lii. p. 146. Otto Volger, "Untersuchungen über die Phänomene der Erdbeben in der Schweiz," Gotha, 1857–8: *Z. Deutsch. Geol. Ges.* xiii. p. 667. K. von Seebach, "Das Mitteldeutsche Erdbeben von 6 März, 1872," Leipzig, 1873. R. Falb, "Grundzüge einer Theorie der Erdbeben und Vulkanensausbrüche," Graz, 1871; "Gedanken und Studien über den Vulkanismus, &c.," 1874. Pfaff, "Allgemeine Geologie als exacte Wissenschaft," Leipzig, 1873, p. 224. Records of observed earthquakes will be found in the memoirs of Mallet and Perrey; also in papers by Fuchs in *Neues Jahrb.* 1865-1871 and in Tschermak's *Mineralog. Mittheilungen*, 1873 and subsequent years. Other papers are quoted in the following pages.

1872 was estimated to have been 2433 feet in a second, that of an earthquake at Travancore in Southern Hindostan 656 feet in a second.

Duration.—The number of shocks in an earthquake varies indefinitely, as well as the length of the intervals between them. Sometimes the whole earthquake only lasts a few seconds; thus the city of Caracas, with its fine churches and 10,000 of its inhabitants, was destroyed in about half-a-minute; Lisbon was overthrown in five minutes. But a succession of shocks of varying intensity may continue for days, weeks, or months. The Calabrian earthquake which began in February, 1783, was continued by repeated shocks for nearly four years until the end of 1786.

Modifying influence of geological structure.—In its passage through the solid terrestrial crust from the focus of origin the earth-wave must be liable to continual deflections and delays, from the varying geological structure of the rocks. To this cause, no doubt, must be ascribed the marked differences in the rate of propagation of the same earthquake in different directions. The wave of disturbance, as it passes from one kind of rock to another and encounters materials of very different elasticity, or, as it meets with joints, dislocations, and curvatures in the same rock, must be liable to manifold changes alike in rate and in direction of movement. Even at the surface one effect of differences of material may be seen in the apparently capricious demolition of certain quarters of a city, while others are left comparatively scatheless. In such cases it is usually found that buildings erected on loose inelastic foundations, such as sand and clay, are more liable to destruction than those placed upon solid rock. In illustration of this statement the accompanying plan (Fig. 64) of Port Royal, Jamaica, was given by De la

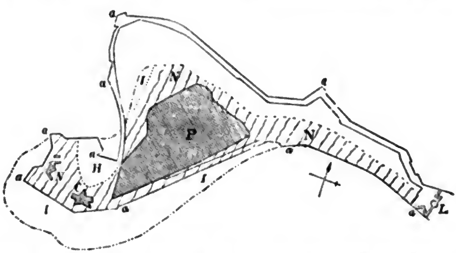

Fig. 64.—Plan of Port Royal, Jamaica, showing the Effects of the Earthquake of 1692 (B.).

P C, Portions of the Town built on Limestone and left standing after the Earthquake; *a a*, L, the Boundary of the Town prior to the Earthquake; N N, Ground gained by the drifting of sand up to the end of last Century; I L H, Additions from the same cause during the first quarter of the present Century.

Beche[1] to show that the portions of the town which did not disappear

[1] "Geological Observer," p. 426.

during the earthquake of 1692 were built upon solid white limestone, while the parts built on sand were shaken to pieces.

It has been observed that an earthquake shock will pass under a limited area without disturbing it, while the region all round has been affected, as if there were there some superficial stratum protected from the earth-wave. Humboldt cited a case where miners were driven up from below-ground by earthquake shocks not perceptible at the surface, and on the other hand, an instance where they experienced no sensation of an earthquake which shook the surface with considerable violence.[1] Such facts bring impressively before the mind the extent to which the course of the earth-wave must be modified by geological structure. In some instances the shock extends outwards from a common centre, so that a series of concentric circles may be drawn round the focus, each of which will denote a certain approximately uniform intensity of shock ("coseismic lines" of Mallet), this intensity of course diminishing with distance from the focus. The Calabrian earthquake of 1857 and that of Central Europe in 1872 may be taken in illustration of this central type. In other cases, however, the earthquake travels chiefly along a certain band or zone without advancing far from it laterally. This type of linear earthquake is exemplified by the frequent shocks which traverse Chili, Peru and Ecuador, between the line of the Andes and the Pacific Coast.

Extent of country affected.—The area shaken by an earthquake varies with the intensity of the shock, from a mere local tract where a slight tremor has been experienced, up to such catastrophes as that of Lisbon in 1755, which, besides convulsing the Portuguese coasts, extended into the north of Africa on the one hand and to Scandinavia on the other, and was even felt as far as the east of North America. Humboldt computed that the area shaken by this great earthquake was four times greater than that of the whole of Europe. The South American earthquakes are remarkable for the great distances to which their effects extend in a linear direction. Thus the strip of country in Peru and Ecuador severely shaken by the earthquake of 1868, had a length of 2000 miles.

Depth of source.—Over the centre of origin the shock is felt as a vertical up-and-down movement (*Seismic vertical* of Mallet). Receding from it in any direction this shock is felt as an undulatory movement and comes up more and more obliquely. The *angle of emergence*, as Mallet showed, may be obtained by taking the mean of observations of the rents and displacements of walls and buildings. In Fig. 65, for example, the wall there represented has been rent by an earthquake which emerged to the surface in the path marked by the arrow.

By observations of this nature Mr. Mallet has shown how it may be possible to estimate approximately the depth of origin of an earthquake. Let Fig. 66, for example, represent a portion of the earth's

[1] "Cosmos," Art. *Earthquakes.*

crust in which at a an earthquake arises. The wave of shock will travel outwards in successive spherical shells. At the point e it will be felt as a vertical movement, and loose objects, such as paving-stones,

Fig. 65.—Wall shattered by an Earthquake, of which the Path of Emergence has been in the Direction shown by the Arrow. (After Mallet.)

may be jerked up into the air, and descend bottom uppermost on their previous sites. At d, however, the wave will emerge at a lower angle, and will give rise to an undulation of the ground, and the oscillation of objects projecting above the surface. In rent buildings the fissures will be on the whole perpendicular to the path of emergence. By a series of observations made at different points, as at g and f, a number of angles are obtained, and the point where the various lines cut the vertical (a) will mark the area of

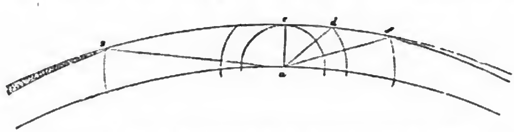

Fig. 66.—Estimation of Source of Earthquake Movements.

origin of the shock. By this means Mallet determined that the depth at which the impulse of the Calabrian earthquake of 1857 was given was about five miles. As the general result of his enquiries he concludes that, on the whole, the origin of earthquakes must be sought in comparatively superficial parts of the crust, probably never exceeding a depth of 30 geographical miles. Von Seebach calculated that the earthquake which affected Central Europe in 1872 originated at a depth of 9·6 geographical miles; that of Belluno in the same year was estimated by Höfer to have had its source rather more than 4

miles deep; while that of Herzogenrath in 1873 was placed by Von Lasaulx at a depth of about 14½ miles.[1]

Geological Effects.—These are dependent not only on the strength of the concussion but on the structure of the ground, and on the site of the disturbance, whether underneath land or sea. They include changes superinduced on the surface of the land, on terrestrial and oceanic waters, and on the relative levels of land and sea.

1. Effects upon the Soil and General Surface of a Country.—The earth-wave or wave of shock underneath a country may traverse a wide region and affect it violently at the time without leaving permanent traces of its passage. Blocks of rock, however, already disengaged from their parent masses, may be rolled down into the valleys below. Landslips are produced, which may give rise to considerable subsequent changes of drainage. In some instances the surfaces of solid rocks are shattered as if by gunpowder, as was particularly noticed in the Concepcion earthquake of 1835 to have taken place among the Primary rocks of that district.[2] It has often been observed also that the soil is rent by fissures which vary in size from mere cracks, like those due to desiccation, up to deep and wide chasms. Permanent modifications of the landscape may thus be produced. Trees are thrown down and buried, wholly or in part, in the rents. These superficial effects may, indeed, be soon effaced by the levelling power of the atmosphere. Where, however, the chasms are wide and deep enough to intercept rivulets, or to serve as channels for heavy rain-torrents, they are sometimes further excavated, so as to become gradually enlarged into ravines and valleys, as has happened in the case of rents caused by the earthquakes of 1811–12, in the Mississippi valley. As a rule, each rent is only a few yards long. Sometimes it may extend for half a mile or even more. In the earthquake which shook the South Island of New Zealand in 1848, a fissure was formed, averaging 18 inches in width and traceable for a distance of 60 miles parallel to the axis of the adjacent mountain-chain. The subsequent earthquake of 1855, in the same region, gave rise to a fracture which could be traced along the base of a line of cliff for a distance of about 90 miles. Dr. Oldham has described a remarkable series of fissurings which ran parallel with the river of Calhar, Eastern British India, varying with it to every point of the compass and traceable for 100 miles.[3]

Remarkable circular cavities have been noticed in Calabria and elsewhere, formed in the ground during the passage of the earth-wave. In many cases these holes serve as funnels of escape for an abundant discharge of water, so that when the disturbance ceases they appear as pools. They are believed to be caused by the sudden collapse of subterranean water-channels and the consequent forcible ejection of the water to the surface.

[1] Höfer, *Sitzb. Akad. Wien*, December 1876. Von Lasaulx, *Das Erdbeben von Herzogenrath am 22 October*, 1873, Bonn, 1874.
[2] Darwin, *Journal of Researches*, 1845, p. 303.
[3] *Q. J. Geol. Soc.* xxviii. p. 257.

2. Effects upon Terrestrial Waters.[1]—Springs are temporarily affected by earthquake movements, becoming greater or smaller in volume, sometimes muddy or discoloured, and sometimes increasing in temperature. Brooks and rivers have been observed to flow with an interrupted course, increasing or diminishing in size, stopping in their flow so as to leave their channels dry, and then rolling forward with increased rapidity. Lakes are still more sensitive. Their waters occasionally rise and fall for several hours, even at a distance of many hundred miles from the centre of disturbance. Thus, on the day of the great Lisbon earthquake, many of the lakes of central and north-western Europe were so affected as to maintain a succession of waves rising to a height of 2 or 3 feet above their usual level. Cases, however, have been observed where, owing to excessive subterranean movement, lakes have been emptied of their contents and their beds have been left permanently dry. On the other hand, areas of dry ground have been depressed, and have become the sites of new lakes.

Some of the most important changes in the fresh water of a region, however, are produced by the fall of masses of rock and earth, which, by damming up a stream, may so arrest its water as to form a lake. If the barrier be of sufficient strength, the lake will be permanent; though from the usually loose, incoherent character of its materials, the dam thrown across the pathway of a stream runs a great risk of being undermined by the percolating water. A sudden giving way of the barrier allows the confined water to rush with great violence down the valley and to produce perhaps tenfold more havoc there than may have been caused by the original earthquake. When a landslip is of sufficient dimensions to divert a stream from its previous course, the new channel thus taken may become permanent, and a valley may be cut out or widened.

3. Effects upon the Sea.—The great sea-wave propagated outward from the centre of a sub-oceanic earthquake, and reaching the land after the earth-wave has arrived there, gives rise to much destruction along the maritime parts of the disturbed region. As it approaches the shore, the littoral waters retreat seawards, sucked up, as it were, by the advancing wall of water, which, reaching a height of sometimes 60 feet, rushes over the bare beach and sweeps inland, carrying with it everything which it can dislodge and bear away. Loose blocks of rock are thus lifted to a considerable distance from their former position, and left at a higher level. Deposits of sand, gravel, and other superficial accumulations are torn up and swept away, while the surface of the country, as far as the limit reached by the wave, is strewn with débris. If the district has been already shattered by the passage of the earth-wave, the advent of the great sea-wave augments and completes the devastation. The havoc caused by the Lisbon earthquake of 1755, and by that of Peru and Ecuador in 1868, was much aggravated by the co-operation of the oceanic wave.

[1] Kluge, *Neues Jahrb.*, 1861, p. 777.

4. Permanent Changes of Level.—It has been observed, after the passage of an earthquake, that the level of the disturbed country has sometimes been changed. Thus after the terrible earthquake of 19th November 1822, the coast of Chili for a long distance was found to have risen from 3 to 4 feet, so that along shore littoral shells were exposed adhering still to the rocks amid multitudes of dead fish. The same coast-line has been further upraised by subsequent earthquake shocks. On the other hand, many instances have been observed where the effect of the earthquake has been to depress permanently the disturbed ground. For example, by the Bengal earthquake of 1762, an area of 60 square miles on the coast, near Chittagong, suddenly went down beneath the sea, leaving only the tops of the higher eminences above water. The succession of earthquakes which in the years 1811 and 1812 devastated the basin of the Mississippi, gave rise to widespread depressions of the ground, over some of which, above alluded to, the river spread so as to form new lakes, with the tops of the trees still standing above the surface of the water.

Distribution of Earthquakes.—While no large space of the earth's surface seems to be free from at least some degree of earthquake-movement, there are regions more especially liable to the visitation. As a rule, earthquakes are most frequent in volcanic districts, the explosions of a volcano being generally preceded or accompanied by tremors of greater or less intensity. In the Old World a great belt of earthquake disturbance stretches in an east and west direction, along that tract of remarkable depressions and elevations lying between the Alps and the mountains of northern Africa, and spreading eastward so as to enclose the basins of the Mediterranean, Black Sea, Caspian, and Sea of Aral, and to rise into the great mountain-ridges of Central Asia. In this zone lie numerous volcanic vents, both active and extinct or dormant, from the Azores on the west to the basaltic plateaux of India on the east. The Pacific Ocean is surrounded with a vast ring of volcanic vents, and its borders are likewise subject to frequent earthquake shocks. Some of the most terrible earthquakes within human experience have been those which have affected the western seaboard of South America.

Origin of Earthquakes.—Though the phenomena of an earthquake become intelligible as the results of the transmission of waves of shock arising from a centre where some sudden and violent impulse has been given within the terrestrial crust, the origin of this sudden blow can only be conjectured. Various conceivable causes may at different times and under different conditions, communicate a shock to the subterranean regions. Such are the sudden flashing into steam of water in the spheroidal state, the sudden condensation of steam, the explosions of a volcanic orifice, the falling in of the roof of a subterranean cavity, or the sudden snap of deep-seated rocks subjected to prolonged and intense strain.

In volcanic regions the frequent earthquakes which precede or accompany eruptions are doubtless traceable to explosions of elastic vapours and notably of steam. As earthquakes originate also in districts remote from any active volcano, and, so far as observation shows, at comparatively shallow depths, these cannot be connected with ordinary volcanic action, though it is possible that by movements of molten or highly-heated matter within the crust and its invasion of the upper layer, to which meteoric water in considerable quantities descends, sudden and extensive generation of steam may occasionally take place.[1] In minor cases where the tremor is slight and local, we may conceive that the collapse of the roof or sides of some of the numerous tunnels and caverns dissolved out of underground rocks by permeating water may suffice to produce the observed shocks. Where, however, the area convulsed is large, some more potent cause must be sought. One of the most abvious of these is the rupture of rocks within the crust under the intense strain produced by subsidence upon the more rapidly contracting inner hot nucleus. In mountainous districts many different degrees of shock from mere tremors up to important earthquakes have been observed, and these are not improbably due to sudden more or less extensive fractures of rocks which are still under great strain.[2] Hoernes, from a study of earthquake phenomena, concludes that though some minor earth-tremors may be due to the collapse of underground caverns, and others of local character to volcanic action, the greatest and most important earthquakes are the immediate consequences of the formation of mountains, and he connects the lines followed by earthquakes with the structural lines of mountain-axes.[3]

A comparison of the dates of recorded earthquakes shows that they have occurred more frequently in the winter half than in the summer half of the year. Out of 656 earthquakes chronicled in France up to the year 1845, three-fifths took place in the winter, and two-fifths in the summer months. In Switzerland also they have been observed to be about three times more numerous in winter than in summer.[4] The same fact is remarked in the history of earthquakes in Britain. The general concurrence of testimony would seem to show that this cannot be an accidental circumstance, though it is not easy to explain how mere differences of atmospheric pressure can affect the stability of the interior of the crust. (See the remarks already made in regard to Stromboli, p. 210.)

Section III.—Secular Upheaval and Depression.

Besides sudden movements due to earthquake-shocks, the crust of the earth undergoes in many places oscillations of an extremely

[1] Pfaff, *Allgemeine Geologie als exacte Wissenschaft*, p. 230.
[2] See *postea*, p. 309. Suess, *Entstehung der Alpen*, Vienna, 1875.
[3] "Erdbeben Studien," *Jahrb. Geol. Reichs.* xxviii. (1878) p. 448.
[4] Perrey, *op. cit.* Perrey and D'Abbadie have likewise tried to trace a connection between the greater frequency of earthquakes and the moon's nearness to the earth.

quiet and uniform character, sometimes of an elevatory, sometimes of a subsiding nature. So tranquil may these changes be as to produce from day to day no appreciable alteration in the aspect of the ground affected, so that only after the lapse of several generations, and by means of careful measurements, can they really be proved. Indeed, in the interior of a country nothing but a series of accurate levellings from some unmoved datum-line might detect the change of level, unless the effects of this terrestrial disturbance showed themselves in altering the drainage. It is only along the sea-coast that a ready measure is afforded of any such movement.

It is customary in popular language to speak of the sea rising or falling relatively to the land. We cannot conceive of any possible augmentation of the oceanic waters, nor of any diminution save what may be due to the extremely slow processes of abstraction by the hydration of minerals and absorption into the earth's interior. Any changes, therefore, in the relative levels of sea and land must be due to some readjustment in the form either of the solid globe or of its watery envelope or of both. Playfair pointed out at the beginning of this century that no subsidence of the sea-level could be local but must extend over the globe.

Various suggestions have been made regarding possible causes of alteration of the sea-level. Thus a shifting of the present distribution of density within the nucleus of the planet would affect the position and level of the oceans (*ante*, p. 44). A change in the earth's centre of gravity, such as might result from the accumulation of large masses of snow and ice as an ice-cap at one of the poles, has been already (p. 18) referred to as tending to raise the level of the ocean in the hemisphere so affected, and to diminish it in a corresponding measure elsewhere. The return of the ice into the state of water would produce an opposite effect. A still further conceivable source of geographical disturbance is to be found in the fact that, as a consequence of the diminution of centrifugal force owing to the retardation of the earth's rotation caused by the tidal wave, the sea-level must have a tendency to subside at the equator and rise at the poles.[1] A larger amount of land, however, need not ultimately be laid bare at the equator, for the change of level resulting from this cause would be so slow that as Dr. Croll has pointed out, the general degradation of the surface of the land might keep pace with it, and diminish the terrestrial area as much as the retreat of the ocean tended to increase it. The same writer has further suggested that the waste of the equatorial land, and the deposition of the detritus in higher latitudes, may still further counteract the effects of retardation and the consequent change of ocean-level.[2]

[1] Croll. *Phil. Mag.* 1868, p. 382. Sir W. Thomson, *Trans. Geol. Soc. Glasgow*, iii. p. 223.

[2] In a recent communication to the 'Geologische Reichsanstalt' of Vienna, Herr Edward Suess has stated his conviction that the limits of the dry land depend upon certain large indeterminate oscillations of the statical figure of the oceanic envelope;

The balance of evidence at present available seems decidedly adverse to any theory which would account for ancient and modern changes in the relative level of sea and land by variations in the figure of the oceanic envelope, but to be in favour of regarding such changes as due to movements of the solid crust. The proofs of upheaval and subsidence, though sometimes obtainable from wide areas, are marked by a want of uniformity and a local and variable character indicative of an action local and variable in its operations, such as the folding of the terrestrial crust, and not uniform and widespread, such as might be predicated of any alteration of sea-level. While admitting therefore that to a certain extent oscillations of the relative level of sea and land may have arisen from some of the causes above enumerated, we must hold that on the whole it is the land which rises and sinks rather than the sea.[1]

§ 1. **Upheaval.**—Various maritime tracts of land have been ascertained to have undergone in recent times, or to be still undergoing, a gradual elevation above the sea. Thus, the coast of Siberia, for 600 miles to the east of the river Lena, the islands of Spitzbergen and Novaja Zemlja, the Scandinavian peninsula with the exception of a small area at its southern apex, and a maritime strip of western South America, have been proved to have been recently upheaved. In searching for proofs of such movements the student must be on his guard against being deceived by any apparent retreat of the sea, which may be due merely to the deposit of gravel, sand, or mud along the shore, and the consequent gain of land. Local accumulations of gravel or "storm beaches" are often thrown up by storms, even above the level of ordinary high-tide mark. In estuaries, also, considerable tracts of low ground are gradually raised above the tide level by the slow deposit of mud. The following proofs of actual rise of the land are chiefly to be relied on.[2]

Evidence from dead organisms.—Rocks covered with barnacles or other littoral adherent animals, or pierced by lithodomous shells, afford presumptive proof of the presence of the sea. A single stone with these creatures on its surface would not be satisfactory evidence, for it might be cast up by a storm; but a line of large boulders, which had evidently not been moved since the cirripedes and molluscs lived upon them, and still more a solid cliff with these marks of littoral or sub-littoral life upon its base, now raised

that not only are "raised beaches" to be thus explained, but that there are absolutely no vertical movements of the crust save such as may form part of the plication arising from secular contraction; and that the doctrine of secular fluctuations in the level of the continents is merely a remnant of the old "Erhebungstheorie," destined to speedy extinction. He is preparing a separate work on the subject, in which he will probably explain how he supposes the oscillations in the equilibrium of the oceans to have been caused. See *Verhand. Geol. Reichs.* 1880, No. 11.

[1] The arguments which can be brought forward against the view above adopted and in favour of the doctrine that the increase of the land above sea-level is due to the retirement of the sea, will be found in an essay by H. Trautschold in the *Bulletin Société Imp. des Naturalistes de Moscou*, xlii. (1869) part i. p. 1.

[2] See "Earthquakes and Volcanoes" (A. G.), Chambers's *Miscellany of Tracts.*

above high-water mark, would be sufficient to demonstrate a rise of land. The amount of the upheaval might be pretty accurately determined by measuring the vertical distance between the upper edge of the barnacle zone upon the upraised rock, and the limit of the same zone on the present shore. By this kind of evidence the recent uprise of the coast of Scandinavia has been proved. The shell borings on the pillars of the temple of Jupiter Serapis in the Bay of Naples prove first a depression and then an elevation of the ground to the extent of more than twenty feet.[1]

Of similar import is the evidence furnished by dead organisms fixed in their position of growth beneath sea-level. Thus dead specimens of *Mya truncata* occur on some parts of the coast of the Firth of Forth in considerable numbers still placed with their siphuncular end uppermost in the stiff clay in which they burrowed. The position of these shells is about high-water mark, but as their existing descendants do not live above low-water mark, we may infer that the coast has been raised by at least the difference between high and low-water mark, or eighteen feet.[2] Shells of the large *Pholas dactylus* occur in a similar position near high-water mark on the Ayrshire coast. Even below low-water examples have been noted, as in the interesting case observed by Sars on the Dröbaksbank in the Christiania Fjord, where dead stems of *Oculina prolifera* (L.) occur at depths of only ten or fifteen fathoms. This coral is really a deep-sea form, living on the western and northern coasts of Norway at depths of one hundred and fifty to three hundred fathoms in cold water. It must have been killed as the elevation of the area brought it up into upper and warmer layers of water.[3] It has even been said that the pines on the edges of the Norwegian snow-fields are dying in consequence of the secular elevation of the land bringing them up into colder zones of the atmosphere.

Any stratum of rock containing marine organisms which have manifestly lived and died where their remains now lie, must be held to prove upheaval of the land. In this way it can be shown that most of the solid land now visible to us has once been under the sea. High on the flanks of mountain chains (as in the Alps and Himalayas), undoubted marine shells occur in the solid rocks.

Sea-worn Caves.—A line of sea-worn caves, now standing at a distance above high-water mark beyond the reach of the sea, affords evidence of recent uprise. In the accompanying diagram (Fig. 67) examples of such caves are seen at the base of the cliff, once the sea-margin, now separated from the tide by a platform of meadow-land.

Raised Beaches furnish one of the most striking proofs of upheaval. A beach, or space between tide-marks, where the sea is

[1] Babbage, *Edin. Phil. Journ.* xi. (1824), 91. J. D. Forbes, *Edin. Journ. Sci.* i. (1829), p. 260. Lyell, "Principles," ii. p. 164.

[2] Hugh Miller's *Edinburgh and its Neighbourhood*, p. 110.

[3] Quoted by Vom Rath in a paper entitled "Aus Norwegen," *Neues Jahrb.* 1869, p. 422. For another example see Gwyn Jeffreys, *Brit. Assoc.*, 1867, p. 431.

constantly grinding down sand and gravel, mingling with them the remains of shells and other organisms, sometimes piling the deposits up, sometimes sweeping them away out into opener water, forms a

Fig. 67.—View of a Line of ancient Sea-cliff pierced at the base with Sea-worn Caves and fronted by a raised Beach.

familiar terrace or platform on coast-lines skirting tidal seas. When land is upraised, and this margin of littoral deposits is carried above the reach of the waves, the flat terrace thus elevated is known as a "raised beach" (Figs. 67, 68). The former high-water mark then lies inland, and while its sea-worn caves are in time hung with ferns and mosses, the beach across which the tides once flowed furnishes a platform, on which meadows, fields, gardens, roads, houses, villages, and towns spring up, while a new beach is made below the margin of the uplifted one.

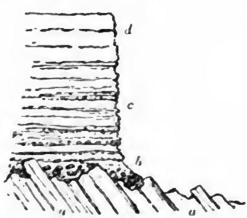

Fig. 68.—Section of a Raised Beach, Composed of Gravel and Sand (b c d) resting on upturned slates (a). Finstrall Bay, Cornwall (B).

Raised beaches abound in the higher latitudes of the northern and southern hemispheres. They are found, for example, round many parts of the coast line of Britain. De la Beche gives the

subjoined view (Fig. 69) of a Cornish locality where the existing beach is flanked by a cliff of slate, *b*, continually cut away by the sea so that the overlying raised beach, *a*, *c*, will ere long disappear.

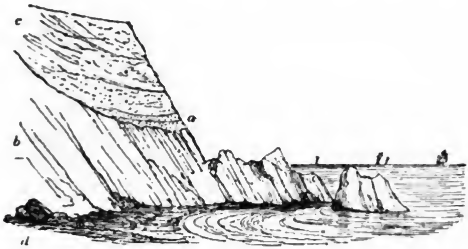

FIG. 69.—VIEW OF RAISED BEACH, NELLY'S CAVE, CORNWALL (B).

The coast-line on both sides of Scotland is likewise fringed with raised beaches, sometimes four or five occurring above each other at heights of 25, 40, 50, 60, 75 and 100 feet above the present high-water mark.[1] The sides of the mountainous fjords of Northern Norway, up to more than 600 feet above sea-level, are marked with conspicuous lines of terraces (Fig. 70), some of which are

FIG. 70.—VIEW OF TERRACES, ALTEN FJORD, NORWAY.

remarkable for showing an increase in their height at a distance of fifty miles inland, and thus indicating a greater upward movement towards the interior than seawards. These terraces are partly

[1] For accounts of some British raised beaches see De la Beche, *Memoir on Geology of Devon and Cornwall*; R. Chambers, "Ancient Sea Margins;" Prestwich, *Q. J. Geol. Soc.* xxviii. p. 38; xxxi. p. 29. Usher, *Geol. Mag.* 1879, p. 166.

ordinary beach deposits, partly notches cut out of rock.[1] Each terrace marks a former lower level of the land with regard to the sea, and probably a lengthened stay of the land at that level, while the intervals between them represent the vertical amount of each successive uplift, and show that the land in its upward movement did not remain long enough at intermediate points for the formation of terraces. A succession of raised beaches, rising above the present sea-level, may therefore be taken as pointing to a former intermittent upheaval of the country, interrupted by long pauses during which the general level did not materially change.

On the west coast of South America lines of raised terrace containing recent shells have been traced by Darwin, which prove a great upheaval of that part of the globe in modern geological time. The terraces are not quite horizontal but rise towards the south. On the frontier of Bolivia they occur at from 65 to 80 feet above the existing sea-level, but nearer the higher mass of the Chilian Andes they are found at 1000, and near Valparaiso at 1300 feet. That some of these ancient sea margins belong to the human period, was shown by Mr. Darwin's discovery of shells with bones of birds, ears of maize, plaited reeds and cotton thread in one of the terraces opposite Callao at a height of 85 feet.[2] Raised beaches occur in New Zealand, and indicate a greater elevation of the southern than the northern part of the country.[3] It should be observed that this increased rise of the terraces polewards occurs both in the northern and southern hemisphere, and is one of the facts insisted upon by those who would explain the terraces by displacements of the sea rather than of the land.

Human Records and Traditions.—In countries which have been long settled by a human population, it is sometimes possible to prove, or at least to render probable, the fact of recent uprise of the land by reference to tradition, to local names, and to works of human construction. Piers and harbours, if now found to stand above the upper limit of high-water, furnish indeed indisputable evidence of a rise of land since their erection. Numerous proofs of a recent upheaval of the coast line of the Arctic Ocean from Spitzbergen eastward have been observed. At Spitzbergen itself, besides its raised beaches, bearing witness to previous elevations, small islands which existed two hundred years ago are now joined to larger portions of land. At Novaja Zemlja since the Dutch expedition of 1594 there seems to have been a rising of the sea bottom to the extent of 100 feet or more. On the north coast of Siberia the island of Diomida,

[1] See R. Chambers, "Tracings of the North of Europe" (1850), p. 172, *et seq.* Bravais, *Voyages de la Commission Scientifique du Nord*, &c., translated in *Q. J. Geol. Soc.* i. p. 534. Kjerulf, *Z. Deutsch. Geol. Ges.* xxii. p. 1. "Die Geologie des süd. und mittl. Norwegen," 1880, p. 7. *Geol. Mag.* viii. p. 74. Dakyns, *Geol. Mag.* 1877, p. 72. Lehmann, "Ueber ehemalige Strandlinien," &c., Halle, 1879. *Zeitsch. ges. Naturwiss.* 1880, p. 280. K. Pettersen, *Tromsö Museums Aarshefter*, III. 1880.

[2] "Geological Observations," chap. ix.

[3] Haast's "Geology of Canterbury," 1879, p. 366.

observed in 1760 by Chalaourof to the east of Cape Sviatoj, was found by Wrangel sixty years afterwards to have been united to the mainland.[1]

§ 2. **Subsidence.** It is more difficult to trace a downward movement of land, for the evidence of each successive sea-margin is carried down and washed away or covered up. The student will take care to guard himself against being misled by mere proofs of the advance of the sea on the land. In the great majority of cases where such an advance is taking place, it is due not to subsidence of the land, but to erosion of the shores. It is indeed the converse of the deposition above mentioned (p. 276) as liable to be mistaken for proof of upheaval. The results of mere erosion by the sea, however, and those of actual depression of the level of the land, cannot always be distinguished without some care. The encroachment of the sea upon the land may involve the disappearance of successive fields, roads, houses, villages, and even whole parishes, without any actual change of level of the land. The following kinds of evidence may be held to prove the fact of subsidence.

Submerged Forests.—As the land is brought down within reach of the waves, and its characteristic surface-features are effaced,

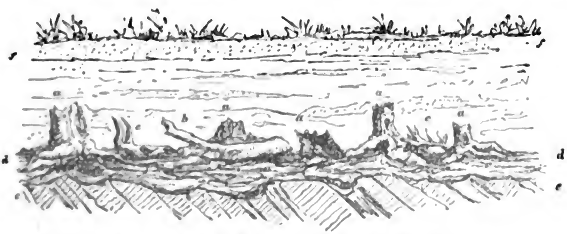

FIG. 71.—SECTION OF SUBMERGED FOREST (B).

A platform of older rocks (*e e*) has been covered with soil (*d d*) on which trees (*a a a*) have established themselves. In course of time, after some of the trees had fallen (*b*), and a quantity of vegetable soil had accumulated, enclosing here and there the bones of deer and oxen (*c c*), the area sank, and the sea overflowing it threw down upon its surface sandy or muddy deposits (*f f*).

the submerged area may retain little or no evidence of its having been a land-surface. It will be covered, as a rule, with sea-worn sand or silt. Hence, no doubt, the reason why, among the marine strata which form so much of the stratified portion of the earth's crust, and contain so many proofs of depression, actual traces of land-surfaces are comparatively rare. It is only under very favourable circumstances, as, for instance, where the area is sheltered from prevalent winds and waves, and where, therefore, the surface of the land can

[1] Grad. *Bull. Soc. Géol. France*, 3rd ser. ii. p. 348. Traces of oscillations of level within historic times have been observed in the Netherlands and Upper Italy. *Bull. Soc. Géol. France*, 2nd ser. xix. p. 556; 3rd ser. ii. pp. 46, 222.

sink tranquilly under the sea, that fragments of that surface may be preserved under overlying marine accumulations. It is in such places that "submerged forests" occur. These are stumps of trees still in their positions of growth in their native soil, often associated with beds of peat, full of tree-roots, hazel-nuts, branches, leaves, and other indications of a terrestrial surface.

De la Beche has described, round the shores of Devon, Cornwall, and western Somerset, a vegetable accumulation, consisting of plants of the same species as those which now grow freely on the adjoining land, and occurring as a bed at the mouths of valleys, at the bottoms of sheltered bays, and in front of and under low tracts of land, of which the seaward side dips beneath the present level of the sea.[1] Over this submerged land-surface sand and silt containing estuarine shells have generally been deposited, whence we may infer that in the submergence the valleys first became estuaries, and then sea-bays. If now, in the course of ages, a series of such submerged forests should be formed one over the other, and if, finally, they should, by upheaval of the sea-bottom, be once more laid dry, so as to be capable of examination by boring, well-sinking, or otherwise, they would prove a former long-continued depression, with intervals of rest. These intervals would be marked by the buried forests, and the progress of depression by the strata of sand and mud lying between them. In short, the evidence would be strictly on a parallel with that furnished by a succession of raised beaches as to a former protracted intermittent elevation.

Coral-islands.—Evidence of wide-spread depression, over the area of the Pacific and Indian Oceans, has been adduced from the structure and growth of coral reefs and islands. Mr. Darwin, many years ago, pointed out that as the reef-building corals do not live at depths of more than 20 to 30 fathoms, and yet their reefs rise out of deep water, the sites on which they have formed those structures may be conceived to have subsided, the rate of subsidence being so slow, that the upward growth of the reef has on the whole kept pace with it.[2] The formation of coral-reefs is described in Book III. Part II. Section iii., and Mr. Darwin's theory is there more fully explained.

Distribution of plants and animals.—Since the appearance of Edward Forbes's essay upon the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected their area,[3] much attention has been given to the evidence furnished by the geographical distribution of plants and animals as to geological revolutions. In some cases the former existence of land now submerged has been inferred with considerable confidence from the distribution of living

[1] "Geology of Devon and Cornwall," *Mem. Geol. Survey*. For further accounts of British submerged forests see *Q. J. Geol. Soc.* xxii. p. 1; xxxiv. p. 447. *Geol. Mag.* vi. p. 76; vii. p. 64; iii. 2nd ser. p. 491; vi. pp. 80, 251.

[2] See Darwin's *Coral Islands*, also Dana's *Corals and Coral Islands*.

[3] *Mem. Geol. Survey*, vol. i. 1846, p. 336.

organisms, although, as Mr. Wallace has shown in the case of the supposed "Lemuria," some of the inferences have been unfounded and unnecessary.[1] The present distribution of plants and animals is only intelligible in the light of former geological changes. As a single illustration of the kind of reasoning from present zoological groupings to former geological subsidence, reference may be made to the fact, that while the fishes and molluscs living in the seas on the two sides of the Isthmus of Panama are on the whole very distinct, a few shells and a larger number of fishes are identical; whence the inference has been drawn that though a broad water-channel originally separated North and South America in Miocene times, a series of elevations and subsidences has since occurred, the most recent submersion having lasted but a short time, allowing the passage of locomotive fishes, yet not admitting of much change in the comparatively stationary molluscs.[2]

Fjords.—An interesting proof of an extensive depression of the north-west of Europe is furnished by the fjords or sea-lochs by which that region is indented. A fjord is a long, narrow, and often singularly deep inlet of the sea, which terminates inland at the mouth of a glen or valley. The word is Norwegian, and in Norway fjords are characteristically developed. The English word "firth," however, is the same, and the western coasts of the British Isles furnish many excellent examples of fjords, such as the Scottish Loch Hourn, Loch Nevis, Loch Fyne, Gareloch; and the Irish Lough Foyle, Lough Swilly, Bantry Bay, Dunmanus Bay. Similar indentations abound on the west coast of British North America. Some of the Alpine lakes (Lucerne, Garda, Maggiore and others), as well as many in Britain, are inland examples of fjords.

There can be little doubt that, though now filled with salt water, fjords have been originally land valleys. The long inlet was first excavated as a valley or glen. The adjacent valley exactly corresponds in form and character with the hollow of the fjord, and must be regarded as merely its inland prolongation. That the glens have been excavated by subaerial agents is a conclusion borne out by a great weight of evidence, which will be detailed in later parts of this volume. If, therefore, we admit the subaerial origin of the glen, we must also grant a similar origin to its seaward prolongation. Every fjord will thus mark the site of a submerged valley. This inference is confirmed by the fact that fjords do not, as a rule, occur singly, but, like glens on land, lie in groups; so that when found intersecting a long line of coast such as that of the west of Norway, or the west of Scotland, they serve to show that the land has there sunk down so as to permit the sea to run far up and fill submerged glens.

Human constructions and historical records.—Should the sea be observed to rise to the level of roads and buildings which

[1] "Island Life," 1880, p. 394. In this work the question of distribution in its geological relations is treated with admirable lucidity and fulness.

[2] Wallace, "Geographical Distribution of Animals," i. pp. 40, 76.

it never used to touch, should former half-tide rocks cease to be visible even at low water, and should rocks, previously above the reach of the highest tide, be turned first into shore reefs, then into skerries and islets, we infer that the coast-line is sinking. Such kind of evidence is found in Scania, the most southerly part of Sweden. Streets, built of course above high-water mark, now lie below it, with older streets lying beneath them, so that the subsidence is of some antiquity. A stone, the position of which had been exactly determined by Linnæus in 1749, was found after 87 years to be 100 feet nearer the water's edge. The west coast of Greenland, for a space of more than 600 miles, is perceptibly sinking. It has there been noticed that, over ancient buildings on low shores, as well as over entire islets, the sea has risen. The Moravian settlers have been more than once driven to shift their boat-poles inland, some of the old poles remaining visible under water.[1] Historical evidence likewise exists of the subsidence of ground in Holland and Belgium.[2]

§ 3. **Causes of Upheaval and Depression of Land.**—These movements must again be traced back mainly to consequences of the internal heat of the earth. There are various ways in which the heat may have acted. As rocks expand when heated, and contract on cooling, we may suppose that, if the crust underneath a tract of land has its temperature slowly raised, as no doubt takes place round areas of nascent volcanoes, a gradual uprise of the ground above will be the result. The gradual transference of the heat to another quarter may produce a steady subsidence. Basing on the calculations of Colonel Totten, cited on p. 319, Lyell estimated that a mass of red sandstone one mile thick, having its temperature augmented 200° Fahr., would raise the overlying rocks 10 feet, and that a portion of the earth's crust of similar character 50 miles thick, with an increase of 600° or 800°, might produce an elevation of 1000 or 1500 feet.[3] Again, rocks expand by fusion and contract on solidification. Hence by the alternate melting and solidifying of subterranean masses, upheaval and depression of the surface may possibly be produced (see *postea*, p. 294).

But processes of this nature can evidently effect changes of level only limited in amount and local in area. When we consider the wide tracts over which terrestrial movements are now taking place, or have occurred in past time, the explanation of them must manifestly be sought in some far more wide-spread and generally effective force in geological dynamics. It must be confessed, however, that no altogether satisfactory solution of the problem has

[1] These observations, which have been accepted for at least a generation past (*Proc. Geol. Soc.* ii. 1835, p. 208), have recently been called in question, but the alleged disproof is not convincing, and they are here retained as worthy of credence. See Suess, *Verhand. Geol. Reichsanstalt*, 1880, No. 11.

[2] Lavaleye, "Affaissement du sol et envasement des fleuves, survenus dans les temps historiques," Brussels, 1859. Grad. *Bull. Soc. Géol. France*, ii. 3rd ser. p. 46. Arends, "Physische Geschichte der Nordseeküste," 1833.

[3] "Principles," ii. p. 235.

yet been given, and that the subject still remains beset with many difficulties.

Mr. George H. Darwin, in one of his recent memoirs already cited (*ante*, p. 20), has suggested a possible determining cause of the larger features of the earth's surface. Assuming for his theory a certain degree of viscosity in the earth, he points out that, under the combined influence of rotation and the moon's attraction, the polar regions tend to outstrip the equator, and to acquire a consequent slow motion from west to east relatively to the equator. The amount of distortion produced by this screwing motion he finds to have been so slow, that 45,000,000 years ago, a point in lat. 30° would have been 4¾′, and a point in lat. 60°, 14¼′ further west, with reference to the equator, than they are at present. This slight transference shows us, he remarks, that the amount of distortion of the surface strata from this cause must be exceedingly minute. But it is conceivable that in earlier conditions of the planet this screwing action of the earth may have had some influence in determining the surface features of the planet. In a body not perfectly homogeneous it might originate wrinkles at the surface running perpendicular to the direction of greatest pressure. "In the case of the earth the wrinkles would run north and south at the equator, and would bear away to the eastward in northerly and southerly latitudes, so that at the north pole the trend would be north-east, and at the south pole north-west. Also the intensity of the wrinkling force varies as the square of the cosine of the latitude, and is thus greatest at the equator and zero at the poles. Any wrinkle, when once formed, would have a tendency to turn slightly, so as to become more nearly east and west than it was when first made."

According to the theory, the highest elevations of the earth's surface should be equatorial, and should have a general north and south trend, while in the northern hemisphere the main direction of the masses of land should bend round towards north-east, and in the opposite hemisphere towards south-east. Mr. Darwin thinks that the general facts of terrestrial geography tend to corroborate his theoretical views, though he admits that some are very unfavourable to them. In the discussion of such a theory, however, we must remember that the present mountain-chains on the earth's surface are not aboriginal, but arose at many successive and widely-separated epochs. Now it is quite certain that the younger mountain-chains (and these include the loftiest on the surface of the globe) arose, or at least received their chief upheaval, during the Tertiary periods—a comparatively late date in geological history. Unless we are to enlarge enormously the limits of time which physicists are willing to concede for the evolution of the whole of that history, we can hardly suppose that the elevation of the great mountain-chains took place at an epoch at all approaching an antiquity of 45,000,000 years. Yet, according to Mr. Darwin's showing, the superficial effects of internal distortion must have been exceedingly minute during the past

45,000,000 years. We must either therefore multiply enormously the periods required for geological changes, or find some cause which could have elevated great mountain-chains at more recent intervals.

But it is well worth consideration whether the cause suggested by Mr. Darwin may not have given their initial trend to the masses of land, so that any subsequent wrinkling of the terrestrial surface due to any other cause would be apt to take place along the original lines. To be able to answer this question it is necessary to ascertain the dominant line of strike of the older geological formations. But information on this subject is still scanty. In Western Europe the prevalent line along which terrestrial plications took place during Palæozoic time was certainly from S.W. or S.S.W. to N.E. or N.N.E., and the same direction is recognizable in the eastern States of North America. But the trend of later formations is more varied. The striking contradictions between the actual direction of so many mountain-chains and masses of land, and what ought to be their line according to the theory, seem to indicate that while the effects of internal distortion may have given the first outlines to the land areas of the globe, some other cause must have been at work in later times, acting sometimes along the original lines, sometimes transverse to them.

The main cause to which geologists are now disposed to refer the corrugations of the earth's surface is secular cooling and consequent contraction. If our planet has been steadily losing heat by radiation into space, it must have progressively diminished in volume. The cooling implies contraction. According to Mr. Mallet, the diameter of the earth is less by at least 189 miles since the time when the planet was a mass of liquid.[1] But the contraction has not manifested itself uniformly over the whole surface of the planet. The crust varies much in structure, in thermal resistance, and in the position of its isogeothermal lines. As the hotter nucleus contracts more rapidly by cooling than the cooled and hardened crust, the latter must sink down by its own weight, and in so doing requires to accommodate itself to a continually diminishing diameter. The descent of the crust gives rise to enormous tangential pressures. The rocks are crushed, crumpled and broken in many places. Subsidence must have been the general rule, but every subsidence would doubtless be accompanied with upheavals of a more limited kind. The direction of these upheaved tracts, whether determined, as Mr. Darwin suggests, by the effects of internal distortion, or by some original features in the structure of the crust, would be apt to be linear. The lines, once taken as lines of weakness or relief from the intense strain, would probably be made use of again and again at successive paroxysms or more tranquil periods of contraction. Mr. Mallet has ingeniously connected these movements with the linear direction of mountain chains, volcanic vents and earthquake shocks. If the initial trend to the land-masses were given as hypo-

[1] *Phil. Trans.* 1873, p. 205.

thetically stated by Mr. Darwin, we may conceive that after the outer parts of the globe had attained a considerable rigidity and could then be only slightly influenced by internal distortion, the effects of continued secular contraction would be seen in the intermittent subsidence of the oceanic basins already existing, and in the successive crumpling and elevation of the intervening stiffened terrestrial ridges.

This view, variously modified, has been widely accepted by geologists as furnishing an explanation of the origin of the upheavals and subsidences of which the earth's crust contains such a long record. But it is not unattended with objections. The difficulty of conceiving that a globe possessing on the whole a rigidity equal to that of glass or steel could be corrugated as the crust of the earth has been, has led some writers to adopt the hypothesis already described (*ante*, p. 53), of an intermediate viscous layer between the solid crust and the solid nucleus, while others have suggested that the observed subsidence may have been caused, or at least aggravated, by the escape of vapours from volcanic orifices. But with modifications the main cause of terrestrial movements is still sought in secular contraction.

Some observers, following an original suggestion of Babbage,[1] have supposed that upheaval and subsidence, together with the solidification, crystallisation, and metamorphism of the layers of the earth's crust, may have been in large measure due to the deposition and removal of mineral matter on the surface. There can be no doubt that the lines of equal internal temperature (isogeothermal lines) for a considerable depth downward, follow approximately the contours of the surface, curving up and down as the surface rises into mountains or sinks into plains. The deposition of a thousand feet of rock will, of course, cause a corresponding rise in the isogeotherms, and if we assume the average rise of temperature to be 1° Fahr. for every 50 feet, then the temperature of the crust immediately below this deposited mass of rock will be raised 20°. But masses of sediment of much greater thickness have been laid down, and we may admit that a much greater increase of temperature than 20° has been effected by this means. On the other hand, the denudation of the land must lead to a depression of the isogeotherms, and a consequent cooling of the upper layers of the crust.

It may be conceded that in so far as the internal structure of rocks may be modified by such progressive increase of temperature as would arise from superficial deposit, this cause of change must have a place in geological dynamics. But it has been urged that besides this effect, the removal of rock by denudation from one area and its accumulation upon another affects the equilibrium of the crust; that the portions where denudation is active, being relieved of weight, rise, while those where deposition is prolonged, being on the contrary loaded, sink. This hypothesis has recently been strongly advocated

[1] *Journ. Geol. Soc.* iii. (1834) p. 206.

by some of the geologists who have been exploring the Western Territories of America, and who point in proof of its truth to evidence of continuous subsidence in tracts where there was prolonged deposition, and of the uprise and curvature of originally horizontal strata over mountain ranges like the Uintah Mountains in Wyoming and Utah, which have been for a long time out of water. To suppose, however, that the removal and deposit of a few thousand feet of rock should so seriously affect the equilibrium of the crust as to cause it to sink and rise in proportion, would evince such a mobility in the earth as could not fail to manifest itself in a far more powerful way under the influence of lunar and solar attraction. That there has always been the closest relation between upheaval and denudation on the one hand, and subsidence and deposition on the other, is undoubtedly true. But denudation has been one of the consequences of upheaval, and deposition has been only kept up by continual subsidence.

We are concerned in the present part of this volume only with the surface features of the land in so far as they bear on questions of geological dynamics. The history of these features will be more conveniently treated in Book VII. after the structure and history of the crust have been described. Before quitting the subject, however, we may observe that the larger terrestrial features, such as the great ocean basins, the lines of submarine ridge surmounted here and there by islands chiefly of volcanic materials, the continental masses of land, and at least the cores of most great mountain chains, are in the main of high antiquity, stamped as it were from the earliest geological ages on the physiognomy of the globe, and that their present aspect has been the result not merely of original hypogene operations but of long-continued superficial action by the epigene forces described at p. 316.

Section IV. Hypogene Causes of Changes in the Texture, Structure, and Composition of Rocks.

The phenomena of hypogene action considered in the foregoing pages relate almost wholly to the effects produced at the surface. It is evident, however, that these phenomena must be accompanied by very considerable internal changes in the rocks which form the earth's outer crust. These rocks, subjected to enormous pressure, have been contorted, crumpled, and folded back upon themselves, as if thousands of feet of solid limestones, sandstones, and shales had been merely a few layers of carpet; they have been shattered and fractured; they have in some places been pushed far above their original position, in others depressed far beneath it: so great has been the compression which they have undergone that their component particles have in many places been re-arranged, and even crystallized. They have here and there actually been reduced to fusion, and have been abundantly invaded by masses of molten rock from below.

In the present section the student is asked to consider chiefly the nature of the agencies by which such changes can be effected; the results achieved, in so far as they constitute part of the architecture or structure of the earth's crust, will be discussed in Book IV. At the outset, it is evident that he can hardly hope to detect many of these processes of subterranean change actually in progress and watch their effects. The very vastness of some of them places them beyond his direct reach, and he can only reason regarding them from the changes which he sees them to have produced. But a good number are of a kind which can in some measure be imitated in laboratories and furnaces. It is not requisite, therefore, to speculate wholly in the dark on this subject. Since the early and classic researches of Sir James Hall, great progress has been made in the investigation of hypogene processes by experiment. The conditions of nature have been imitated as closely as possible, and varied in different ways, with the result of giving us an increasingly clear insight into the physics and chemistry of subterranean geological changes. The following pages are chiefly devoted to an illustration of the nature of hypogene action, in so far as that can be inferred from the results of actual experiment. The subject may be conveniently treated under three heads—1. The effects of mere heat; 2. the influence of the co-operation of heated water; 3. the effects of pressure and contraction.

§ 1.—Effects of Heat.

The importance of heat among the transformations of rocks has been fully admitted by geologists, since it used to be the watchword of the Huttonian or Vulcanist school at the end of last century. Two sources of subterranean heat may have at different times and in different degrees co-operated in the production of hypogene changes—the original internal heat of the globe, and the heat due to the transformation of mechanical energy in the crumpling, fracturing, and crushing of the rocks of the crust.

Rise of temperature by depression.—As stated above, the mere recession of rocks from the surface owing to superposition of newer deposits upon them will cause the isogeotherms, or lines of equal subterranean temperature, to rise—in other words, will raise the temperature of the masses so withdrawn. This can take place, however, to but a limited extent unless combined with such depression of the crust as to admit of thick sedimentary formations. From the rate of increment of temperature downwards it is obvious that at no great depth the rocks must be at the temperature of boiling water, and that farther down, but still at a distance which relatively to the earth's radius is small, they must reach and exceed the temperatures at which they would fuse at the surface. Mere descent to a great depth, however, will not necessarily result in any marked lithological change, as has been shown in the cases of the Nova Scotian and South Welsh coal-fields, where sandstones,

shales, clays, and coal-seams can be proved to have been once depressed 14,000 to 17,000 feet below the sea-level, under an overlying mass of rock, and yet to have sustained no serious alteration. They must have been kept for a long period exposed to a temperature of at least 212° Fahr. Such a temperature would have been sufficient to set some degree of internal change in progress had any appreciable quantity of water been present, whence the absence of any alteration may perhaps be explicable on the supposition that these rocks were comparatively dry (p. 298).

Rise of temperature by rock-crushing.—But a further store of heat is provided by the internal crushing of rocks during the collapse and re-adjustment of the crust. The amount of heat so produced has been made the subject of direct experiment. Daubrée has shown that, by the mutual friction of its parts, firm brick-clay can be heated in three-quarters of an hour from a temperature of 18° to one of 40° C. (65° to 104° Fahr.)[1] The most elaborate and carefully-conducted series of experiments yet made in this subject are those conducted by Mr. Mallet. He subjected 16 varieties of stone (limestone, marble, porphyry, granite and slate) in cubes averaging rather less than 1½ inches in height to pressures sufficient to crush them to fragments, and estimated the amount of pressure required, and of heat produced. The following examples may be selected from his table.[2]

Rock.	Temperature (Fahr.) in 1 cubic foot of rock due to work of crushing.	Number of cubic feet of water at 32 deg. evaporated into steam at 212 deg.	Volume of ice at 32 deg. melted to water at 32 deg. by one volume of rock.
Caen Stone, Oolite	8°·004	0·0046	0·04008
Sandstone, Ayre Hill, Yorkshire .	47°·79	0·0234	0·2026
Slate, Conway	132°·85	0·07	0·596
Rowley Rag (basalt)	213°·23	0·109	0·925
Granite, Aberdeen	155°·94	0·072	0·617
Scotch furnace clay porphyry . .	198°·97	0·083	0·724

Within the crust of the earth, there are abundant proofs of enormous stresses under which the rocks have been crushed. The weight of rock involved in these movements has often been that of masses several miles thick. We can conceive that the heat thus generated may have been sufficient to promote many chemical and mineralogical re-arrangements through the operation of water (*postea*,

[1] *Géol. Expérimentale*, p. 448, *et seq*. This distinguished chemist and geologist has during the last forty years devoted much time to researches designed to illustrate experimentally the processes of geology. His numerous important memoirs are scattered through the *Annales des Mines*, *Comptes Rendus de l'Académie*, *Bulletin de la Société Géologique de France*, and other publications. But he has recently collected and republished as *Etudes Synthétiques de Géologie Expérimentale*, 8vo, 1879—a storehouse of information. The admirable memoirs of Delesse in the same journals should also be studied.

[2] *Phil. Trans*. 1873, p. 187.

p. 298), and may even have been here and there enough for the actual fusion of the rocks by the crushing of which it was produced.

Rise of temperature by intrusion of erupted rock.—The great heat of lava, even when examined at the surface of the earth, has been already referred to, and some examples have been given of its effects (p. 227). Where it does not reach the surface, but is injected into subterranean rents and passages, it must effect considerable changes upon the rocks with which it comes in contact. That such intruded igneous rocks have sometimes melted down portions of the crust in their passage can hardly be doubted. But probably still more extensive changes may take place from the exceedingly slow rate of cooling of erupted masses, and the consequently vast period during which their heat is being conveyed through the adjacent rocks. Allusion will be made in later pages to the observed amount of such "contact metamorphism" (Book IV. Part VIII.).

Expansion.—Rocks are dilated by heat. The extent to which this takes place has been measured with some precision for various kinds of rock, as shown in the subjoined table.

Rock.	Expansion for every 1° Fahr.	Authority.
Black marble, Galway, Ireland .	·00000247	Adie, *Trans. Roy. Soc. Edin.* xiii. p. 366.
Grey granite, Aberdeen. . . .	·00000438	*Ibid.*
Slate, Penrhyn, Wales	·00000576	*Ibid.*
White marble, Sicily	·00000613	*Ibid.*
Red sandstone, Portland, Connecticut	·00000963	Totten, *Amer. Journ. Sci.* xxii. 136.

According to these data the expansion of ordinary rocks ranges from about 2·47 to 9·63 millionths for 1° Fahr. Even ordinary daily and seasonal changes of temperature suffice to produce considerable superficial changes in rocks (see p. 319). The much higher temperatures to which rocks are exposed by subsidence within the earth's crust must have far greater effects. Some experiments by Pfaff in heating from an ordinary temperature up to a red heat, or about 1180° C., small columns of granite from the Fichtelgebirge, red porphyry from the Tyrol, and basalt from Auvergne, gave the expansion of the granite as 0·016808, of the porphyry 0·012718, of the basalt 0·01199[1]. The expansion and contraction of rocks by heating and cooling have been already referred to as possible sources of upheaval and depression (p. 284).

Crystallization (Marble).—In the experiments of Sir James Hall, pounded chalk, hermetically enclosed in gun-barrels and exposed to the temperature of melting silver, was melted and partially crystallized, but still retained its carbonic acid. Chalk,

[1] *Z. Deutsch. Geol. Ges.* xxiv. p. 403.

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similarly exposed, with the addition of a little water, was reduced to the state of marble.[1] These experiments have recently been repeated by G. Rose, who has produced by dry heat from lithographic limestone and chalk, fine-grained marble without melting. The distinction of marble is the independent crystalline condition of its component granules of calcite. This structure, therefore, can be superinduced by heat under pressure. In nature, portions of limestone which have been invaded by intrusive masses of igneous rock have been converted into marble, the gradations from the unaltered into the altered rock being distinctly traceable, as will be shown in subsequent pages (Book IV. Part VIII.).

Production of Prismatic Structure.—The long-continued high temperature of iron-furnaces has been observed to have superinduced a prismatic or columnar structure upon the hearth-stones. This fact is of interest in geology, seeing that sandstones and other rocks in contact with eruptive masses of igneous matter have at various depths below the surface assumed a similar internal arrangement (Book IV. Part VIII.).

Fusion.—In an interesting series of experiments the illustrious De Saussure (1779) fused some of the rocks of Switzerland and France, and inferred from them, contrary to the opinion previously expressed by Desmarest,[2] that basalt and lava have not been produced from granite, but from hornstone (pierre de corne), varieties of "schorl," calcareous clays, marls, and micaceous earths, and the cellular varieties from different kinds of slate.[3] He observed, however, that the artificial products obtained by fusion were glassy and enamel-like, and did not always recall volcanic rocks, though some exactly resembled porous lavas. Dolomieu (1788) also contended that as an artificially-fused lava becomes a glass and not a crystalline mass with crystals of easily fusible minerals, there must be some flux present in the original lava, and he supposed that this might be sulphur.[4]

Sir James Hall, about the year 1790, began an important investigation, in which he succeeded in reducing various ancient and modern volcanic rocks to the condition of glass, and in restoring them, by slow cooling, to a stony state.[5] Since that time many other researches of a more complicated kind have been undertaken, especially by Delesse, Daubrée, Deville, Bunsen, Bischof, H. and W. B. Rogers. By these observations it has been abundantly proved that all rocks undergo molecular changes when exposed to high temperature, that when the heat is sufficiently raised they become fluid, that if the glass thus obtained is rapidly cooled it remains vitreous, and that, if allowed to cool slowly, a more or less distinct

[1] *Trans. Roy. Soc. Edin.* vi. (1805), p. 101, 121.
[2] *Mem. Acad. Scien.* 1771, p. 273.
[3] De Saussure, *Voyages dans les Alpes*, edit. 1803, tome i. p. 178.
[4] *Isles Ponces*, p. 8 *et seq.*
[5] *Trans. Roy. Soc. Edin.* v. p. 43.

crystallisation sets in, the glass is devitrified, and a lithoid product is the result.

Illustrations of the influence of different degrees of heat upon rocks of various kinds may often be very instructively observed at lime-kilns, especially those roughly-built kilns or pits which may still be met with in outlying districts. Some of the stones lining such cavities will be found with no sensible change, others show a somewhat cellular, others a rudely prismatic structure, while some have had their surfaces fused into a rough glaze or enamel. The bricks or stones used for lining furnaces present similar illustrations. In these and other effects, when produced by the contact of hot intruded igneous rocks, the alteration is merely local, and has obviously been produced either by contact with a highly-heated surface, or through the operation of heated vapours escaping from the eruptive mass. But, besides such minor effects due to contact, others of a more general kind affect large masses of rock or whole districts of country (Book IV. Part VIII.).

The effect of heat in the open air upon different minerals varies considerably. Thus a few, such as native arsenic and calomel, pass into vapour without melting and form sublimates. But many refractory substances may be made to sublimate in the presence of other vapours, in particular, of fluorine and boron (see p. 302). Some minerals (sulphur, for example) pass at once, others (like mica, olivine, and hornblende), almost at once, from the liquid into the solid condition, as water does in freezing. The majority, however, after fusion, have an intermediate viscous stage, like that of iron and glass. Many minerals can be made to crystallize again after fusion (augite, garnet, calcite, rock-salt, fluor-spar), or can be artificially produced by the melting together of their component ingredients (augite, apatite, pyromorphite); others, however, remain in an amorphous vitreous condition.[1]

A glass is an amorphous substance resulting from fusion, perfectly isotropic in its action on transmitted polarized light (*ante*, pp. 99, 189). Its specific gravity is rather lower than that of the same substance in the crystallized condition. By being allowed to cool slowly, or being kept for some hours at a heat which softens it, glass assumes a dull porcelain-like aspect. This devitrification possesses much interest to the geologist, seeing that most volcanic rocks, as has been already (p. 104) described, present the characters of devitrified glasses. It consists in the appearance of minute crystallites, and other imperfect or rudimentary crystalline forms, accompanied with an increase of density and diminution of volume. It must be regarded as an intermediate stage between the perfectly glassy and the crystalline conditions.

Rocks exposed to temperatures as high as their melting-points fuse into glass which, in the great majority of cases, is of a bottle-green or black colour, the depth of the tint depending mainly on the

[1] Roth, *Chem. Geol.* i. p. 40.

proportion of iron. In this respect they resemble the natural glasses —pitchstones and obsidians. They almost always contain minute cells or bubbles, arising probably from the disengagement of water or of oxygen. But after the most thorough fusion which has been found possible, minute granules usually appear in the solidified glass. Sometimes these consist of specks of quartz (which from its refractory nature is especially apt to remain unmelted) or of other minerals of the original rock.[1]

Microscopic investigation of artificially-fused rocks shows that, even in what seems to be a tolerably homogenous glass, there are abundant minute hair-like, feathered, needle-shaped, or irregularly-aggregated bodies diffused through the glassy paste. These crystallites, in some cases colourless, in others opaque, metallic oxides, particularly oxides of iron, resemble the crystallites observed in many volcanic rocks (p. 100). They may be obtained even from the fusion of a granitic or granitoid rock, as in the well-known case of the Mount Sorrel syenite near Leicester, which, being fused and slowly cooled, yielded to Mr. Sorby abundant crystallites, including exquisitely-grouped octohedra of magnetite.[2]

According to the observations of Delesse, volcanic rocks, when reduced to a molten condition, attack briskly the sides of the Hessian crucibles in which they are contained, and even eat them through. This is an interesting fact, for it helps to explain how some intrusive igneous rocks have come to occupy positions previously filled by sedimentary strata, and why, under such circumstances, the composition of the same mass of rock should be found to vary considerably from place to place.[3]

Contraction of Rocks in passing from a Glassy to a Stony State.—Reference has been made (pp. 284, 291) to the expansion of rocks by heat and their contraction on cooling; likewise to the difference between their volume in the molten and in the solid state. It would appear that this diminution in density as rocks pass from a crystalline into a vitreous condition, is, on the whole, greater the more silica and alkali are present, and is less as the proportion of iron, lime, and alumina increases. According to Delesse, granites, quartziferous porphyries, and such highly silicated rocks lose from 8 to 11 per cent. of their density when they are reduced to the condition of glass, basalts lose from 3 to 5 per cent., and lavas, including the

[1] One of the basalts of Arthur's Seat, Edinburgh, after exposure to a high temperature for four hours, was supposed to be completely fused; but was found on examination with the microscope to have retained its large labradorite crystals, only partially rounded on the edges and otherwise unaffected.

[2] Zirkel, *Mik. Besch.* p. 92; Sorby, *Address Geol. Sect. Brit. Assoc.* 1880. On the microscopic structure of slags, &c., see Vogelsang's "Krystalliten."

[3] *Bull. Soc. Géol. France*, 2nd ser., iv. 1382; see also *Trans. Edin. Roy. Soc.* xxix. p. 492. Bischof has described a series of experiments on the fusion of lavas with different proportions of clay-slate. He found that the lava of Niedermendig kept an hour in a bellows-furnace was reduced to a black glassy substance without pores, and that a similar product was obtained even after 30 per cent. of clay-slate had been added and the whole had been kept for two hours in the furnace. *Chem. und Phys. Geol.* Supp. (1871), p. 98.

vitreous varieties, from 0 to 4 per cent.[1] More recently Mr. Mallet has observed that plate glass (taken as representative of acid or siliceous rocks) in passing from the liquid condition into solid glass contracts 1·59 per cent., 100 parts of the molten liquid measuring 98·41 when solidified; while iron-slag (having a composition not unlike that of many basic igneous rocks) contracts 6·7 per cent., 100 parts of the molten mass measuring 93·3 when cold.[2] By the contraction due to such changes in the internal condition of subterranean masses of rock minor oscillations of level of the surface may be accounted for, as already stated (p. 284). Thus the vitreous solidification of a molten mass of siliceous rock 1000 feet thick might cause a subsidence of about 16 feet, while, if the rock were basic, the amount of subsidence might be 67 feet.

Difference between the products of artificial fusion and natural lavas.—In the experiments of De Saussure, Dolomieu, Hall, and subsequent observers, it has been found impossible to obtain from a piece of fused rock a crystalline substance exactly resembling the original mass. Externally it may appear quite stony, but its internal structure, as revealed by the microscope, shows it to be essentially a slag or glass, and not a truly crystalline rock. There is another fundamental difference between the natural and artificial products. When a compound containing substances of different fusibilities is artificially melted, and allowed thereafter to cool in such a way that the various ingredients may separate from each other, they appear in their order of fusibility, the most refractory coming first, and the most fusible being the last to take a solid form. But in rocks which have crystallized naturally from a fluid condition, it is often to be observed that the component minerals have been far from obeying what might have been supposed to be their invariable law. Thus, in all parts of the world, granite presents the very striking fact that its quartz, which we call an infusible mineral, has actually solidified after the more fusible felspar. In the Vesuvian lavas the difficultly fusible leucite may be seen to have enclosed crystals already formed of the fusible augite. In some ancient crystalline rocks the pyroxenic constituents, which offer a less resistance to fusion, have assumed a crystalline form before the more refractory triclinic felspars. From these facts it is clear that, in the fusion of rocks and in their subsequent consolidation, there have been conditions under which the normal order of appearance of the minerals might be disturbed or reversed.

Yet another fact may be mentioned to show further the difference between the kind of fusion which has frequently obtained in nature

[1] *Bull. Soc. Géol. France*, 1847, p. 1390. Bischof had determined the contraction of granite to be as much as 25 per cent. (*Leonhard und Bronn Jahrb.* 1841). The correctness of this determination was disputed by D. Forbes (*Geol. Mag.* 1870, p. 1), who found from his own experiments that the amount of contraction must be much less. The values given were still so much in excess of those recently obtained with much care by Mallet, that some defect in their determination may be suspected.

[2] *Phil. Trans.* clxiii. pp. 201, 204; clxv.; *Proc. Roy. Soc.* xxii. p. 328.

and that of the ordinary operations of a glass-work or iron-furnace. As far back as the year 1846, Scheerer observed that there exist in granite various minerals which could not have consolidated save at a comparatively low temperature. He instanced especially gadolinites, orthites, and allanites, which cannot endure a higher temperature than a dull-red heat without altering their physical characters; and he concluded that granite, though it may have possessed a high temperature, cannot have solidified from simple igneous fusion.[1]

We may conclude, therefore, that the confessedly igneous rocks of the earth's crust, though they can be shown to have been in a fluid or pasty state, have not solidified from that mere simple fusion which we can accomplish artificially, but that conditions have been involved which have not been successfully imitated in any laboratory or furnace. We may infer also that in the modifications of rock structure and texture, short of actual fusion, simple dry heat has not been the active agent.

Three obvious differences present themselves between the natural and artificial operations. (1.) The element of time must be taken into account; igneous rocks, more particularly the portions of them which consolidated beneath the surface, have cooled vastly more slowly than any artificial product. (2.) Rocks which have undoubtedly once been in a liquid, others that may have consolidated from a pasty condition, and some which have been injected as veins and dykes into previously consolidated masses, contain water imprisoned within their component crystals. This is not water subsequently introduced. Ocular demonstration of the abundance of water in the molten magma beneath the crust is furnished by the enormous discharges of steam from volcanoes, and from many erupted lavas, long after they have congealed (p. 198). In the crystals of recent lava, as well as in those of early geological periods, the presence of water in minute cavities may be readily detected (p. 96). It is contained in microscopic cells within the component minerals, and was enclosed with its gases and saline solutions at the time when these minerals crystallized out of their parent magma. The quartz of granite is usually full of such water-vesicles. "A thousand millions," says Mr. J. Clifton Ward, "might easily be contained within a cubic inch of quartz, and sometimes the contained water must make up at least 5 per cent. of the whole volume of the containing quartz." Thus microscopic investigation confirms the conclusion arrived at by Scheerer in the memoir already cited, that at the time of its eruption granite must have been a kind of pasty mass containing a considerable proportion of water. It is common now to speak of the "aquo-igneous" origin of some eruptive rocks, and to treat their production as a part of what are termed the "hydro-thermal" operations of geology. We may conclude that, while some rocks, like obsidian and pitchstone, which so closely resemble artificial glasses, may have

[1] *Bull. Soc. Géol. France*, iv. p. 468.

been derived from a simple igneous fusion such as can be imitated in a furnace (though even in these the presence and influence of water may be traced), the vast majority of rocks have had a more complex origin, and in a great number of cases can be proved to have been mingled with more or less water while they were still fluid. Some of the operations of the contained water, so far as they can be inferred from experiment, are stated at p. 298. (3.) There can be no question that, in the great hypogene laboratory of nature, rocks have been softened and fused under enormous pressure. Besides the pressure due to their varying depth from the surface, they must have been subject to the enormous expansion of the superheated water or vapour which filled all their cavities, and sometimes, also, to the compression resulting from the secular contraction of the globe and consequent corrugation of the crust. Mr. Sorby inferred that in many cases the pressure under which granite consolidated must have been equal to that of an overlying mass of rock 50,000 feet, or more than 9 miles, in thickness, while De la Vallée Poussin and Renard from other data deduced a pressure equal to 87 atmospheres (p. 97). It is not probable that any such thick overlying mass ever did cover the granite.

If, therefore, any conclusion may be safely based upon the concurrent testimony of experiment, it would appear that perfect anhydrous fusion, or the reduction of a rock to the state of a completely homogeneous glass, has been a comparatively rare process in nature, or at least that such glasses, if originally formed, have in the vast majority of cases undergone devitrification and crystallization, until the glassy base has been reduced to a fraction of the total mass of the rock, or has entirely passed into a stony condition. Besides the obsidians and other natural glasses, traces of an original vitreous base can be readily observed with the microscope between the definitely-formed crystals of many igneous rocks. But in such rocks as granite, no glass exists, nor any trace of the crystallites so generally found as accompaniments of the vitreous condition. Doubtless such differences point to original distinctions in the kind and degree of fusion of the rocks. It seems reasonable to suppose that those rocks which show a glassy ground-mass, and the presence of crystallites, have been fused under conditions more nearly resembling those of the simple igneous fusion of experiment.

Sublimation.—It has long been known that many mineral substances can be obtained in a crystalline form from the condensation of vapours (p. 202). This process, called Sublimation, may be the result of the mere cooling and reappearance of bodies which have been vaporised by heat and solidify on cooling, or of the solution of these bodies in other vapours or gases, or of the reaction of different vapours upon each other. These operations, of such common occurrence at volcanic vents, and in the crevices of recently erupted and still hot lava-streams, have been successfully imitated by experiment. In the early researches of Sir James Hall on the effects

of heat modified by compression, he obtained by sublimation "transparent and well-defined crystals," lining the unoccupied portion of a hermetically-sealed iron tube, in which he had placed and exposed to a high temperature some fragments of limestone.[1] Numerous experiments have been made by Delesse, Daubrée, and others, in the production of minerals by sublimation. Thus, many of the metallic sulphides found in mineral veins have been produced by exposing to a comparatively low temperature (between that of boiling water and a dull-red heat) tubes containing metallic chlorides and sulphide of hydrogen. By varying the materials employed, corundum, quartz, apatite, and other minerals have been obtained. It is not difficult, therefore, to understand how, in the crevices of lava-streams and volcanic cones, as well as in mineral veins, sulphides and oxides of iron and other minerals may have been formed by the ascent of heated vapours. Superheated steam is endowed with a remarkable power of dissolving that intractable substance, silica; artificially heated to the temperature of the melting point of cast-iron, it rapidly attacks silica, and deposits the mineral in snow-white crystals as it cools. Sublimation, however, can hardly be conceived as having operated in the formation of rocks, save here and there in the infilling of open fissures.

§ 2. Influence of Heated Water—Metamorphism.

In the geological contest fought at the beginning of the century between the Neptunists and the Plutonists, the two great battle-cries were, on the one side, Water, on the other, Fire. The progress of science since that time has shown that each of the parties had some truth on its side, and had seized one aspect of the problems touching the origin of rocks. If subterranean heat has played a large part in the construction of the materials of the earth's crust, water, on the other hand, has performed a hardly less important share of the task. They have often co-operated together, and in such a way that the result must be regarded as their joint achievement, wherein the respective share of each can hardly be exactly apportioned. In Part II. of this Book the chemical operation of infiltrating water at ordinary temperatures at the surface and among rocks at limited depths is described. We are here concerned mainly with the work done by water when within the influence of subterranean heat.

Presence of water in all rocks.—By numerous observations it has been proved that all rocks within the accessible portion of the earth's crust contain interstitial water, or, as it is sometimes called, quarry-water (*eau de carrière*). This is not chemically combined with their mineral constituents, nor hermetically sealed up in vesicles, but is merely retained in their pores. Most of it evaporates when the stone is taken out of the parent rock and freely exposed to the atmosphere. The absorbent powers of rocks vary greatly, and chiefly

[1] *Trans. Roy. Soc. Edin.* vi. p. 110.

in proportion to their degree of porosity. Gypsum absorbs from about 0·50 to 1·50 per cent. of water by weight; granite, about 0·37 per cent.; quartz from a vein in granite, 0·08; chalk, about 20·0; plastic clay, from 19·5 to 24·5. These amounts may be increased by exhausting the air from the specimens and then immersing them in water.[1]

The interstitial water of igneous rocks may be either an original constituent, deriving its origin, like any of the component minerals, from molten reservoirs within the earth's crust, or may have descended from the surface. Many facts may be adduced in support of the greater probability of the second view. Besides the general proximity of volcanic orifices to large sheets of water, we have abundant evidence of the actual descent of water from the surface, both through fissures, and also by permeation through the solid substance of rocks. All surface rocks contain water, and no mineral substance is strictly impervious to the passage of this liquid. The well-known artificial colouring of agates proves that even mineral substances apparently the most homogeneous and impervious can be traversed by liquids. In the series of experiments above (p. 263) referred to, Daubrée has illustrated the power possessed by water of penetrating rocks, in virtue of their porosity and capillarity, even against a considerable counter-pressure of vapour; and, without denying the presence of original water, he concludes that the interstitial water of igneous rocks may all have been derived by descent from the surface.

The masterly researches of Poiseuille have shown that the rate of flow of liquids through capillaries is augmented by heat. He proves that water at a temperature of 45° C. in such situations moves nearly three times faster than at a temperature of 0° C. At the high temperatures under which the water must exist at some depth within the crust, its power of penetrating the capillary interstices of rocks must be increased to such a degree as to enable it to become a powerful geological agent.[2]

Solvent power of water among rocks.—The presence of interstitial water must affect the chemical constitution of rocks. It is now well understood that there is probably no terrestrial substance which, under proper conditions, is not to some extent soluble in water. By an interesting series of experiments, made many years ago by Messrs. Rogers, it was ascertained that ordinary mineral constituents of rocks could be dissolved to an appreciable extent even by distilled water, and that the change was accelerated and augmented by the presence of carbonic acid.[3] Water, as pure as it ever occurs in a natural state, can hold in solution appreciable proportions of

[1] See an interesting paper by Delesse, *Bull. Soc. Géol. France*, 2me sér. xix. (1861-2) p. 65.

[2] *Comptes Rendus* (1840), xi. p. 1048. Pfaff (*Allgemeine Geologie*, p. 141) concludes from his calculations as to the relations between pressure and tension that water may descend to any depth in fissures and remain in a fluid state even at high temperatures.

[3] *American Journ. Science* (2), v. p. 401.

silica, alkaliferous silicates, and iron oxide even at ordinary temperatures. The mere presence, therefore, of water within the pores of subterranean rocks cannot but give rise to changes in the composition of these rocks. Some of the more soluble materials must be dissolved, and, as the water evaporates, must be redeposited in a new form.[1]

This power increased by heat.—The chemical action of water is increased by heat, which may be either the earth's original heat or that which arises from internal crushing of the crust. Mere descent from the surface into successive isogeotherms raises the temperature of permeating water until it may greatly exceed the boiling point. But a high temperature is not necessary for many important mineral rearrangements. Daubrée has proved that very moderate heat, not more that 50° C. (122° Fahr.) has sufficed for the production of zeolites in Roman bricks by the mineral waters of Plombières.[2] He has experimentally demonstrated the vast increase of chemical activity of water with augmentation of its temperature, by exposing a glass tube containing about half its weight of water to a temperature of about 400° C. At the end of a week he found the tube so entirely changed into a white, opaque, powdery mass as to present not the least resemblance to glass. The remaining water was highly charged with an alkaline silicate containing 63 per cent. of soda and 37 per cent. of silica, with traces of potash and lime. The white solid substance was ascertained to be composed almost entirely of crystalline materials, partly in the form of minute perfectly limpid bipyramidal crystals of quartz, but chiefly of very small acicular prisms of wollastonite. It was found, moreover, that the portion of the tube which had not been directly in contact with the water was as much altered as the rest, whence it was inferred that at these high temperatures and pressures the vapour of water acts chemically like the water itself.

Co-operation of pressure.—The effect of pressure must be recognized as most important in enabling water, especially when heated, to dissolve and retain in solution a larger quantity of mineral matter than it could otherwise do.[3] In Daubrée's experiments just cited, the tubes were hermetically sealed and secured against fracture, so that the pressure of the greatly superheated vapour had full effect. By this means, with alkaline water, he not only produced the two minerals above mentioned, but also felspar and diopside. The enormous pressures under which many crystalline rocks have solidified is indicated by the liquid carbon dioxide in the vesicles of their crystals.

Experiments in metamorphism.—Besides showing the solvent power of super-heated water and vapour upon glass in illustration of

[1] See further on this subject, Part II. p. 353.
[2] *Géologie Expérimentale*, p. 462.
[3] Sorby has shown that the solubility of all salts which exhibit contraction in solution is remarkably increased by pressure. *Proc. Roy. Soc.* (1862–3), p. 340.

what happens within the crust of the earth, Daubrée's experiments possess a high interest and suggestiveness in regard to the internal rearrangements and new structures which water may superinduce upon rocks. Hermetically sealed glass tubes containing scarcely one-third of their weight of water and exposed for several days to a temperature below an incipient red heat, showed not only a thorough transformation of structure into a white, porous, kaolin-like substance, encrusted with innumerable bipyramidal crystals of quartz like those of the drusy cavities of rocks, but had acquired a very distinct fibrous and even an eminently schistose structure. The glass was found to split readily into concentric laminæ arranged in a general way parallel to the original surfaces of the tube, and so thin that ten of them could be counted in a breadth of a single millimetre. Even where the glass though attacked retained its vitreous character, these fine zones appeared like the lines of an agate. The whole structure recalled that of some schistose and crystalline rocks. Treated with acid the altered glass crumbled and permitted the isolation of certain nearly opaque globules and of some minute transparent infusible acicular crystals or microliths, sometimes grouped in bundles and reacting on polarized light. Reduced to thin slices and examined under the microscope with a magnifying power of 300 diameters, the altered glass presented: 1st, Spherulites, $\frac{5}{10}$ of a millimetre in radius, nearly opaque, yellowish, bristling with points which perhaps belong to a kind of crystallization, and with an internal radiating fibrous structure (these resist the action of concentrated hydrochloric acid, whence they cannot be a zeolite, but may be a substance like chalcedony); 2nd, innumerable colourless acicular microliths, with a frequently stellate, more rarely solitary distribution, resisting the action of acid like quartz or an anhydrous silicate; 3rd, dark green crystals of pyroxene (diopside). Daubrée satisfied himself that these enclosures did not pre-exist in the glass, but were developed in it during the process of alteration.[1]

Scheerer, Élie de Beaumont, and Daubrée have shown how the presence of a comparatively small quantity of water in eruptive igneous rocks may have contributed to suspend their solidification, and to promote the crystallization of their silicates at temperatures considerably below the point of fusion and in a succession different from their relative order of fusibility. In this way the solidification of quartz in granite after the crystallization of the silicates, which would be unintelligible on the supposition of mere dry fusion, becomes explicable, likewise the enclosure of highly fusible augite in the nearly infusible leucite of some Italian lavas. The water may be

[1] *Géol. Expérim.* p. 158 *et seq.* The production of crystals and microliths in the devitrification of glass at comparatively low temperatures by the action of water is of great interest. The first observer who described the phenomenon appears to have been Brewster, who, in the second decade of this century, studied the effect upon polarized light of glass decomposed by ordinary meteoric action. (*Phil. Trans.* 1814. *Trans. Roy. Soc. Edin.* xxii. (1860) p. 607. See on the weathering of rocks, Part II. of this Book, p. 333.)

regarded as a kind of mother-liquor out of which the silicates crystallize apart from relative fusibility.

But beside the effects from increase of temperature and pressure we have to take into account the fact that water in a natural state is never chemically pure. In its descent through the air it absorbs in particular oxygen and carbon dioxide, and filtering through the soil it abstracts more of this oxide as well as other results of decomposing organic matter. It is thus enabled to effect numerous decompositions of subterranean rocks even at ordinary temperatures and pressures. But as it continues its underground journey and obtains increased solvent power, the very solutions it takes up augment its capacity for effecting mineral transformations. The influence of dissolved alkaline carbonates in promoting the decomposition of many minerals was long ago pointed out by Bischof. In 1857 Sterry Hunt showed by experiments that water impregnated with these carbonates would, at a temperature of not more than 212° Fahr., produce chemical reactions among the elements of many sedimentary rocks, dissolving silica and generating various silicates.[1] Daubrée likewise proved that in presence of dissolved alkaline silicates at temperatures above 700° Fahr. various siliceous minerals, as quartz, felspar and pyroxene, could be crystallized, and that at this temperature these silicates would combine with kaolin to form felspar.[2]

The presence of fluorine has been proved experimentally to have a remarkable action in facilitating some precipitates, especially tin oxides, as well as in other parts of the mechanism of mineral veins.[3] Further illustrations of the important part probably played by this element in the crystallization of some minerals and rocks have been published by St. Claire Deville and Hautefeuille, who by the use of compounds of fluorine have obtained such minerals as rutile, brookite, anatase and corundum in crystalline form.[4] É. de Beaumont inferred that the mineralizing influence of fluorine had been effective even in the crystallization of granite. He believed that "the volatile compound enclosed in granite, before its consolidation contained not only water, chlorine, and sulphur, like the substance disengaged from cooling lavas, but also fluorine, phosphorus and boron, whence it acquired much greater activity and a capacity for acting on many bodies on which the volatile matter contained in the lavas of Etna has but a comparatively insignificant action."[5]

Application of experimental results to the theory of the metamorphism of rocks.—In a large number of instances it is doubtless quite impossible to say from which of the various sources of hypogene heat above enumerated, or from what combination of

[1] *Phil. Mag.* xv. p. 68.
[2] *Bull. Soc. Géol. France*, xv. p. 103.
[3] First suggested by Daubrée, *Ann. des Mines* (1841), 3me sér. xx. p. 65.
[4] *Comptes Rendus*, xlvi. p. 764 (1858); xlvii. p. 89; lvii. p. 648 (1865).
[5] *Sur les Emanations Volcaniques et Métallifères*, *Bull. Soc. Géol. France*, iv. (1846), p. 1249. This admirable and exhaustive memoir, one of the greatest monuments of É. de Beaumont's genius, should be consulted by the student.

them, that elevation of temperature has proceeded of which the metamorphism of rocks may be regarded as one result. Looking at the question in its broadest aspect and without reference to the special source of heat, we can perceive four conditions which must have largely determined internal rearrangements in rocks. (1) The temperature, from the lowest at which any change is possible up to that of complete fusion; (2) the nature of the materials operated upon, some being much more susceptible of change from heat than others; (3) the pressure under which the heat acted, the potency of its action being much increased with increase of pressure; (4) the presence of water usually containing various mineral solutions, whereby chemical changes might be effected which would not be possible in dry heat.

Since experiment has proved that in presence of water under pressure, even at comparatively low temperatures, mineral substances are vigorously attacked, we may expect to find that as these conditions abundantly exist within the earth's crust, the rocks exposed to them have been more or less altered. A large proportion of the accessible crust consists of sedimentary materials which were laid down on the ocean bottom, and which were abundantly soaked with sea-water even after they had been covered over with more recent formations. The gradual growth of the submarine accumulations would of course deprive the lower strata of most of their original water, but some proportion of it would probably remain. If, according to Dana, the average amount of interstitial water in stratified rocks, such as limestones, sandstones, and shales, be assumed to be 2·67 per cent., which is probably less than the truth, "the amount will correspond to two quarts of water for every cubic foot of rock."[1] There is certainly a considerable store of water ready for chemical action when the required conditions of heat and pressure are obtained. We must also remember that as the water in which the sedimentary formations of the crust were formed was mostly that of the ocean, it already possessed chlorides, sulphates, and other salts with which to begin its reactions. The inference may therefore be drawn that rocks possessing not more than 3 per cent. of interstitial water cannot be depressed to depths of several thousand feet beneath the level of the earth's surface, and undergo great pressure and crushing, without suffering more or less marked internal change or metamorphism.

A metamorphosed rock is one which has suffered such a mineralogical rearrangement of its substance. It may or may not have been a crystalline rock originally. Any rock capable of alteration (and all rocks must be so in some degree) will, when subjected to the required conditions, become metamorphic. The resulting structure, however, will, in most cases, bear witness to the original character of the mass. In some cases the change has consisted merely in the rearrangement or crystallization of one mineral originally present, as

[1] Manual, 3rd ed. (1880), p. 758.

in limestone converted into marble; in others it has involved the introduction of mineral solutions, and the partial or complete transformation of the original constituents, whether crystalline or clastic, into new crystalline minerals. Quartz-rock is evidently a compacted sandstone, either hardened by mere pressure, or most frequently by the deposit of silica between its granules, or a slight solution of these granules by permeating water so that they have become mutually adherent. A clay-slate is a hardened, cleaved, and somewhat altered form of muddy sediment, which on the one hand may be found full of organic remains like any common shale, while on the other it may be traced becoming more and more crystalline until it passes into chiastolite-slate, or some other crystalline rock. Yet remains of the fossils may be obtained even in the same hand-specimens with crystals of andalusite, garnet, or other minerals. The calcareous matter of corals is sometimes replaced by hornblende, garnet, and axinite without deformation of the fossils.[1]

A few illustrative examples of metamorphism may be given here; the structure of metamorphic rocks, with the phenomena of "regional" and "contact" metamorphism, will be discussed in Book IV., Part VIII.

Production of Marble from Limestone.—One of the most obvious cases of alteration—the conversion of ordinary limestone into crystalline saccharoid marble—has been already (p. 291) referred to.[2] The calcite having undergone complete transformation, its original structure, whether organic or not, has been effaced, and a new structure has been developed consisting of an aggregate of minute rounded grains, each with an independent crystalline arrangement. The production of a crystalline structure in amorphous calcite, may be effected by the action of mere meteoric water at or near the surface (*ante*, p. 166 and *postea*, p. 353). But the generation of the peculiar granular structure of marble always demands heat and pressure and probably usually the presence of water; the details of the process are, however, still involved in obscurity. We know that where a dyke of basalt or other intrusive rock has involved limestone, it has sometimes been able to convert it for a short distance into marble. The heat (and perhaps the moisture) of the invading lava have sufficed to produce a granular structure, which even under the microscope is identical with that of marble. The conversion of wide areas of limestone into marble is a regional metamorphism associated usually with the alteration of other sedimentary masses into schists, &c.

Dolomitization.—Another alteration which from the labours of Von Buch received in the early decades of this century much attention from geologists is the conversion of ordinary limestone into dolomite. Some dolomite appears to be an original chemical precipitate from the saline water of inland seas (Part II. Sect. ii. § 4). But

[1] *Ann. des. Mines*, 5me sér. xii. p. 318.
[2] See also "Marmarosis" in Book IV. Part VIII.

calcareous formations due to organic secretions are often weakly dolomitic at the time of their formation, and may have their proportion of magnesium carbonate increased by the action of permeating water, as is proved by the conversion into dolomite of shells and other organisms, consisting originally of calcite or aragonite and forming portions of what was no doubt originally a limestone, though now a continuous mass of dolomite. This change may have sometimes consisted in the mere abstraction of carbonate of lime from a limestone already containing carbonate of magnesia, so as to leave the rock in the form of dolomite; or probably more usually in the action of the magnesium salts of sea-water, especially the chloride, upon organically formed limestone; or sometimes locally in the action of a solution of carbonate of magnesia in carbonated water upon limestone, either magnesian or non-magnesian. Élie de Beaumont calculated that on the assumption that one out of every two equivalents of carbonate of lime was replaced by carbonate of magnesia, the conversion of limestone into dolomite would be attended with a reduction of the volume of the mass to the extent of 12·1 per cent. It is certainly remarkable in this connection that large masses of dolomite which may be conceived to have once been limestone have the cavernous, fissured structure, which on this theory of their origin might have been looked for.

Dolomite has been produced both on a small and on a great scale. In the north of England and elsewhere, the Carboniferous Limestone has been altered for a few feet or yards on either side of its joints into a dull yellow dolomite, locally termed "dunstone." Similar vertical zones of dolomite occur also in the Carboniferous Limestone of the South of Ireland, together with beds of magnesian limestone, interstratified with the ordinary limestone. Harkness pointed out that the vertical ribs occur where the rocks are much jointed, and the beds where they have few or no joints.[1] No doubt mere percolating water has in these instances been the agent of change. On the other hand, there occur great regions of dolomite with a crystalline structure, which, like that of the Eastern Alps, has by some writers been regarded as altered ordinary limestone. In all probability, however, these masses became dolomite at the beginning by the action of the magnesian salts of the concentrated waters of inland seas upon organic or inorganic calcareous deposits accumulated previous to the concentration, their metamorphism having consisted mainly in the subsequent generation of a crystalline structure analogous to that of the conversion of limestone into marble.[2]

Conversion of Vegetable Substance into Coal.—Exposed to the atmosphere, dead vegetation is decomposed into humus, which

[1] *Q. J. Geol. Soc.* xv. p. 100.

[2] On dolomitization, see L. von Buch, in Leonhard's *Mineralog. Taschenbuch.* 1824; Nauman's *Geognosie*, i. p. 763; Bischof's *Chemical Geology*, iii.; Elie de Beaumont, *Bull. Soc. Geol.* viii. (1836), p. 174. Sorby, *Brit. Assoc. Rep.* 1856, part ii. p. 77, and *Address Q. J. Geol. Soc.* 1879. A full statement of the literature of this subject will be found in a suggestive memoir by C. Doelter and R. Hoernes, *Jahrb. Geol. Reichsanstalt*, xxv.

goes to increase the soil. But sheltered from the atmosphere, exposed to the action of water, especially with an increase of temperature, and under some pressure, it is converted into lignite and coal. An example of this alteration was observed a few years ago in the Dorothea mine, Clausthal. Some of the timber in a long-disused level, filled with slate rubbish, and saturated with the mine-water from decomposing pyrites, was found to have a leathery consistence when wet, but, on exposure to the air, hardened to a firm and ordinary brown-coal, which had the typical brown colour and external fibrous structure, with the internal fracture, of a black glossy pitch-coal.[1] This change must have been produced within less than four centuries—the time since the levels were opened. According to Bischof's determinations the conversion of wood into coal may take place, 1st, by the separation of carbonic acid and carburetted hydrogen; 2nd, by the separation of carbonic acid and the formation of water either from oxidation of hydrogen by meteoric oxygen or from the hydrogen and oxygen of the wood; 3rd, by the separation of carbonic acid, carburetted hydrogen and water.[2] The circumstances under which the vegetable matter now forming coal has been accumulated were favourable for this slow transmutation. The carbon-dioxide (choke-damp) of old coal-mines and the carburetted hydrogen (fire-damp CH_4), given off in such large quantities by coal seams, are products of the alteration which would appear to be accelerated by terrestrial movements such as those that compress and plicate rocks. During the process these gases escape, and the proportion of carbon progressively increases in the residue, till it reaches the most highly mineralized anthracite (p. 172), or may even pass into nearly pure carbon or graphite. In the coal-basins of Mons and Valenciennes the same seams which are in the state of bituminous coal (*gras*) at the surface gradually lose their volatile constituents as they are traced downward till they pass into anthracite. In the Pennsylvanian coal-field the coals become more anthracitic as they are followed into the eastern region, where the rocks have undergone great plication, and where, possibly during the subterranean movements, they were exposed to an elevation of temperature.[3] Daubrée has produced from wood, exposed to the action of superheated water, drop-like globules of anthracite which had evidently been melted in the transformation, and which presented a close resemblance to the anthracite of some mineral veins.[4]

Production of the Schistose Structure.—All rocks are not equally permeable by water, nor is the same rock equally permeable in all directions. Among the stratified rocks especially, which form so large a proportion of the visible terrestrial crust, there are great differences in the facility with which water can travel, the planes of sedimentation being naturally those along which water passes most

[1] Hirschwald, *Z. Deutsch. Geol. Ges.* xxv. p. 364.
[2] Bischof, *Chem. Geol.* i. p. 274.
[3] Daubrée, "Géologie Expérimentale," p. 463.
[4] *Op. cit.* p. 177.

easily. It is in these planes that the differences of mineral structure and composition are ranged. Layers of siliceous, argillaceous, and calcareous material alternate, each varying in porosity and capability of being changed by permeating water. We may, therefore, expect that unless the original stratified structure has been effaced or rendered inoperative by any other superinduced structure, it will guide the metamorphic action of underground water, and will remain more or less distinctly traceable, even after very considerable mineralogical transformations have taken place. Even without this guiding influence, superheated water can produce a schistose structure, as Daubrée's experiments upon glass, above cited, have proved.

The stratified formations consist largely of silica, silicates of alumina, lime, magnesia, soda, potash, and iron oxides. These mineral substances exist there as original ingredients, partly in recognizable worn crystals, but mainly in a granular or amorphous condition, ready to be acted on by permeating water under the requisite conditions of temperature and pressure. We can understand that any re-combination and re-crystallization of the silicates will probably follow the laminæ of deposit, and that in this way a crystalline foliated structure may be developed. Round masses of granite erupted among Palæozoic rocks, instructive sections may be observed where a transition can be traced from ordinary unaltered sedimentary strata, such as sandstones, greywackes and shales containing fossils, into foliated crystalline rocks to which the names of mica-schist and gneiss may be applied. (Book IV., Part VIII.) Not only can the gradual change into a crystalline foliated structure be readily followed with the naked eye, but with the aid of the microscope the finer details of the alteration can be traced. Minute plates of some micaceous mineral and small concretions of quartz or felspar may be observed to have crystallized out of the surrounding amorphous sediment. These can be seen gradually increasing in size and number until the rock assumes a thoroughly foliated structure and passes into a true schist. Yet even in such a schist traces of the original and durable water-worn quartz-granules may be detected.[1] Foliation is thus a crystalline segregation of the mineral matter of a rock in certain dominant planes which are probably for the most part those of original stratification, but may in some cases be those of joints or of cleavage.[2] Mr. Sorby has recognized foliation in these three sets of planes even among the same rocks.[3]

Scrope many years ago called attention to the analogy between the foliation of schists and the ribbanded or streaky structure of trachyte, obsidian and other lavas.[4] This analogy has even been

[1] Sorby, *Q. J. Geol. Soc.* xxxvi. p. 82.
[2] Darwin, "Geological Observations," p. 162. Ramsay, "Geology of North Wales," in *Memoirs of Geol. Survey*, vol. iii. p. 182.
[3] *Op. cit.* p. 84.
[4] "Volcanoes," pp. 140, 300.

regarded as an identity of structure, and the idea has found supporters that the schistose rocks have been in a condition similar to or identical with that of many volcanic masses and have acquired their peculiar fissility by differential movements within the viscous or pasty magma, the solidified minerals being drawn out into layers in the direction of motion. Daubrée, availing himself of the researches of Tresca on the flow of solids (*postea*, p. 313), has endeavoured to imitate artificially some of the phenomena of foliation by exposing clay and other substances to great but unequal pressure.[1] It is inconceivable, however, that such changes could have been produced over the vast areas occupied by foliated rocks. At the same time, the intense corrugation and crumpling of these rocks deserves in this connection attentive consideration.

A relation can, indeed, be commonly traced between the completeness of the crystalline schistose structure and the extent of the corrugation, the most highly puckered masses being also as a rule the most crystalline. So universal is this relation as to show that crumpling and foliation stand in close connection with each other. The inference seems reasonable that the intense compression of the masses, as maintained by Mr. Mallet, has been attended with the generation of sufficient heat to allow of the observed chemical and mineralogical rearrangements.

In some places the schistose structure disappears and is replaced by one of a thoroughly amorphous kind, indistinguishable from that of ordinary eruptive rocks. Where this has taken place veins or injected portions of the amorphous rock may be observed penetrating the adjoining highly crystalline foliated masses. It is in such cases difficult to avoid the conclusion that these intrusive veins are really portions of the foliated rocks reduced to the ultimate stage of crystalline rearrangement, every trace of foliation or original structure having been effaced, and the rocks having been brought into a plastic condition, in which, during the crumpling of the crust, they were actually forced into cracks of the less highly altered members of their own series. There is no essential distinction between gneiss and granite, save the foliated structure of the one and the amorphous structure of the other. But gneiss in a plastic state and squeezed into fissures, or between beds of firmer consistence, would doubtless consolidate as granite.

Thus the study of metamorphism and metamorphic rocks leads us from unaltered stratified deposits at the one end into true eruptive masses at the other. We are presented with a cycle of change wherein the same particles of mineral matter pass from igneous rocks into sedimentary deposits, then by increasing stages of alteration back into crystalline amorphous masses like the original rocks, whence, after being reduced to detritus and re-deposited in sedimentary formations, they may be once more launched on a similar series of transformations. The phenomena of metamorphism appear to be

[1] "Géologie Expérimentale," p. 410.

linked together with those of igneous action as connected manifestations of hypogene change. The author has further suggested a relation between periods of extensive metamorphism and periods of volcanic eruption. He has pointed out that in the geological history of Britain there are indications of such a relation, the volcanic eruptions of the Old Red Sandstone period, for example, succeeding the time when the Silurian rocks of the Scottish Highlands were crumpled and metamorphosed.[1]

§ 3. Effects of pressure.

Besides the influence of pressure in raising the melting point of rocks, and in permitting water to remain fluid among them at very high temperatures, we have to consider the effects produced by the same cause upon rocks already solidified. The most obvious result of pressure is consolidation, as where a mass of loose sand is gradually compacted into a more or less coherent stone, or where, with accompanying chemical changes, a layer of vegetation is compressed into peat, lignite, or coal. The cohesion of a sedimentary rock may be due merely to the pressure of the superincumbent strata, but some cementing material has usually contributed to bind the component particles together. Of these natural cements the most frequent are peroxide of iron, silica, and carbonate of lime.

Pressure equally distributed over a rock presenting everywhere nearly the same amount of resistance will promote consolidation, but may produce no further internal change. If, however, the pressure becomes extremely unequal, or if the rock subjected to it can find escape from the strain in one or more directions, there may be a rupture in the continuity of the mass or a rearrangement of its particles, which by this means are made to move upon each other. Five consequences of these movements may be briefly alluded to here in illustration of hypogene action in dynamical geology. A fuller account of their effects in the general structure of rock-masses will be found in Book IV.

(1.) **Minor Ruptures and Noises.**—Among mountain valleys, in railway tunnels through hilly regions, or elsewhere among rocks subjected to much lateral pressure, sounds as of explosions are occasionally heard. These noises are probably the result of relief from great lateral compression. The rocks have for ages been in a state of strain, from which, as denudation advances, or as artificial excavations are made, they are relieved, and this relief takes place, not always uniformly, but sometimes cumulatively by successive shocks or snaps. Mr. W. H. Niles of Boston has described a number of interesting cases where the effects of such expansion could be seen in quarries; large blocks of rock being rent and crushed into fragments, and smaller pieces being even discharged with explosion

[1] *Trans. Geol. Soc. Edin.* ii. p. 287.

into the air.[1] If this is the condition of rocks even at the surface we can realize that at great depths, where escape from strain is for long periods impossible, and the compression of the masses must be enormous, any sudden relief from this strain may well give rise to an earthquake-shock (p. 273). A continued condition of strain must also influence the solvent power of water permeating the rocks (p. 300).

(2.) **Cleavage.**—When a mass of rock, owing to subsidence or any other cause, is subjected to powerful lateral compression, its innate particles, which have almost invariably a longer and shorter axis, tend, under the intense strain, to rearrange themselves in the line of least resistance, that is, with their long axes perpendicular to the direction of the pressure, whereby a fissile structure is developed. Examined microscopically a section of a rock thus influenced shows (Fig. 72) a striking contrast to its original character (Fig. 73).

Fig. 72.—Section of Compressed Argillaceous Rock in which cleavage structure has been developed. Magnified.

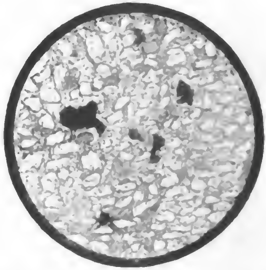

Fig. 73.—Section of a similar Rock which has not undergone this modification. Magnified.

Rocks which have been thus acted on, and have acquired this superinduced fissility, are said to be c l e a v e d, and the fissile structure is termed c l e a v a g e. In Fig. 74, for example, where the

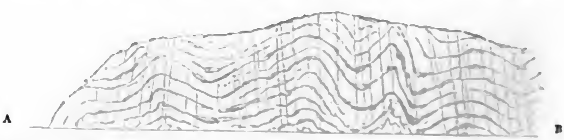

Fig. 74.—Curved Quartz-rocks traversed by vertical and highly-inclined Cleavage. South Stack Lighthouse, Anglesea (*B.*).

original planes of stratification of the rocks are represented by wavy lines, and the new system of cleavage planes by fine upright lines,

[1] *Proc. Boston Soc. Nat. Hist.* xviii. p. 272 (1876).

the strata, at first in even parallel beds, have been subjected to great compression from the directions (A) and (B), in consequence of which they have been thrown into folds, while their minute particles have been forced to rearrange themselves perpendicularly to the pressure. Hence the rocks are both crumpled and cleaved. The fineness of the cleavage depends in large measure upon the texture of the original rock. Sandstones, consisting as they do of rounded obdurate quartz-grains, take either a very rude cleavage or none at all. Fine-grained argillaceous rocks, consisting of minute particles or flakes, that can adjust their long axes in a new direction, are those in which the structure is best developed. In a series of cleaved rocks, therefore, cleavage may be perfect in argillaceous beds (*b b*, Figs. 75 and 76),

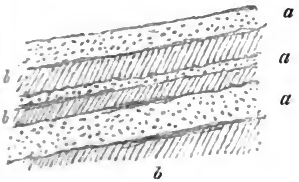

FIG. 75.

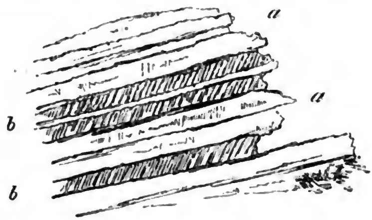

FIG. 76.

DEPENDENCE OF CLEAVAGE UPON THE GRAIN OF THE ROCK (*B.*).

and imperfect or absent in interstratified beds of sandstone (*a a*, Fig. 75) or of limestone (as at Clonea Castle, Waterford, *a a*, Fig. 76).

That cleavage has really been produced in this mechanical way by lateral pressure has been proved experimentally by Sorby, who effected perfect cleavage in pipeclay through which scales of oxide of iron had previously been mixed.[1] Tyndall superinduced cleavage on bees-wax and other substances by subjecting them to severe pressure. Cleavage among rocks occurs on a great scale in countries where the strata have been much plicated, that is, where they now occupy much less horizontal surface than they once did, having been subjected to powerful lateral pressure, in accommodating themselves to their diminished area. The structure of districts with cleaved rocks is described in Book IV. Part V.

(3.) **Deformation.**—Further evidence of the compression to which rocks have been subjected is furnished by the way in which contiguous pebbles in a conglomerate may be found to have been squeezed into each other, and even sometimes to have been elongated in a certain general direction. It is doubtless the coarseness of the grain of such rocks which permits the effects of compression to be so readily seen. Similar effects may take place in fine-grained

[1] *Edin. New Phil. Journ.* lv. (1853), p. 137. The student will find recent interesting additions to our knowledge of the microscopic structure and the history of cleaved rocks in Mr. Sorby's address, *Q. J. Geol. Soc.* xxxvi. p. 72.

rocks and escape observation. Daubrée has imitated experimentally indentations produced by the contiguous portions of conglomerate pebbles.[1]

In discussing the cause of these indentations it must be remembered that imprints of pebbles upon each other, particularly when the material is limestone or other tolerably soluble rock, may have been to some extent produced by solution taking place most actively where pressure was greatest. But there are other indubitable evidences of actual deformation within the mass of a rock, proving a certain degree of mobility even in what would be termed solid and brittle rocks. Of these evidences, perhaps the most instructive and valuable are furnished by the remains of plants and animals occurring as fossils. Where fossiliferous rocks have undergone great compression, and have suffered internal rearrangement, the extent of this movement can be measured in the resultant distortion of the fossils. In Figs. 77 and 79 drawings are given of two

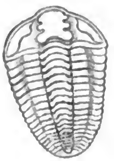

Fig. 77.—A Trilobite (*Calymene Blumenbachii*), natural shape.

Fig. 78.—The same Trilobite, altered by deformation—Lower Silurian, Hendre Wen, near Cerrig y Druidion, North Wales. (*B.*)

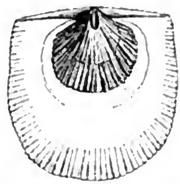

Fig. 79.—A Brachiopod (*Strophomena expansa*), natural shape.

Lower Silurian fossils in their natural forms. In Fig. 78 a specimen of the same species of trilobite as in Fig. 77 is represented where it has been distorted during the compression of the enclosing rock. In Fig. 80 four examples of the same shell as in Fig. 79 are shown greatly distorted by a strain which has elongated the rock in the direction *a b*.

Another illustration of the effects of pressure in producing deformation in rocks, is supplied by the so-called "lignilites,"

[1] *Comptes Rendus*, xliv. p. 823; also his *Géologie Expérimentale*, Part I. sect. ii. chap. iii. where a series of important experiments on deformation is given. For various examples and opinions, see Rothpletz, *Z. Deutsch. Geol. Ges.* xxxi. p. 355. Heim, *Mechanismus der Gebirgsbildung*, 1878, vol. ii. p. 31. Hitchcock, *Geology of Vermont*, i. p. 28. *Proc. Bost. Soc. Nat. Hist.* vii. pp. 209, 353; xviii. p. 97; xv. p. 1; xx. p. 313. *Amer. Assoc.* 1866, p. 83. *Amer. Journ. Sci.* (2) xxxi. p. 372.

"epsomites," or "stylolites." These are cylindrical or columnar bodies varying in length up to more than four inches, and in diameter to two or more inches. The sides are longitudinally striated or grooved. Each column, usually with a conical or rounded cap of clay, beneath which a shell or other organism may frequently be detected, is placed at right angles to the bedding of the limestones, or calcareous shales

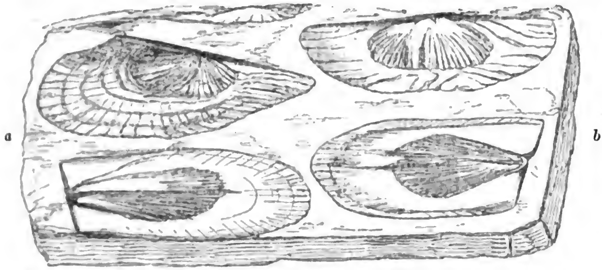

FIG. 80.—*Strophomena expansa*, ALTERED BY THE DEFORMING INFLUENCE OF CLEAVAGE—LOWER SILURIAN, CWM IDWAL, CAERNARVONSHIRE. (*B.*)

through which it passes, and consists of the same material. This structure has been referred by Professor Marsh to the difference between the resistance offered by the column under the shell, and by the surrounding matrix to superincumbent pressure. The striated surface in this view is a case of "slickensides." The same observer has suggested that the more complex structure known as "Cone in cone" may be due to the action of pressure upon concretions in the course of formation.[1]

The ingenious experiments of M. Tresca[2] on the flow of solids have thrown considerable light upon these internal deformations of rock-masses. He has proved that, even at ordinary atmospheric temperatures, solid resisting bodies like lead, cast-iron, and ice, may be so compressed as to undergo an internal motion of their parts, closely analogous to that of fluids. Thus, a solid jet of lead has been produced by placing a piece of the metal in a cavity between the jaws of a powerful compressing machine. Iron, in like manner, has been forced to flow in the solid state into cavities and take their shape. On cutting sections of the metals so compressed, their particles or crystals are found to have ranged themselves in lines of flow which follow the contour of the space into which they have been squeezed. Such experiments are of considerable geological interest. They suggest that in certain circumstances, under great pressure, the unequally mixed particles of rocks within the earth's crust may

[1] *Proc. American Assoc. Science*, 1867.
[2] *Comptes Rendus*, 1864, p. 754; 1867, p. 809. *Mém. Sav. Étrangers*, xviii. p. 733 xx. p. 75. *Inst. Mech. Engineers*, June, 1867; June, 1878.

not only have been forced to rearrange themselves as in cleavage structure, but to move upon each other to such a degree as to acquire a "fluxion-structure" resembling that seen in rocks which have possessed true liquidity (p. 104). No large sheet of rock can be expected, however, to have undergone this internal change; the effects would probably be produced only here and there at places where there was an escape from the pressure, as, for instance, along the sides of fissures,[1] or in other cavities of rocks. As already remarked, this explanation ought not to be applied to the case of rocks like schists, which display foliation like a kind of fluxion-structure over areas many hundreds of square miles in extent.[2]

4. **Plication.**—On the assumption of a more rapid contraction of the inner hot nucleus of the globe, and the consequent descent of the cool upper shell, a subsiding area requires to occupy less horizontal space, and must therefore suffer powerful lateral compression. The rocks will thus be crumpled, as, in the classic experiment of Sir James Hall (Fig. 81), layers of cloth are folded when a weight is

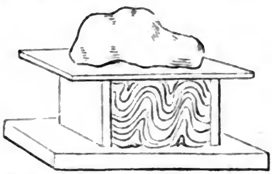

Fig. 81.—Hall's Experiment illustrating contortion.

placed upon them and they are squeezed from either side.[3] The mere subsidence of such a curved surface as that of our globe must thus necessarily produce much lateral compression with consequent contortion.[4] De la Beche long ago pointed out that if contorted and tilted beds were levelled out, they would require more space than can now be obtained for them without encroaching on other areas.[5] The magnificent example of the Alps brings before the mind the enormous extent to which the crust of the earth has in some places been compressed. According to the measurements and estimates of Professor Heim of Zurich, the diameter of the northern zone of the central Alps is only about one half of the original horizontal extent of the component strata which have been corrugated and thrown back upon each other in huge folds reaching from base to summit of lofty mountains, and spreading over many square miles of surface.

[1] See the remarks made under "Segregation Veins," Book IV. Part VII. § i.

[2] See Daubrée, "Géol. Expérim." i. p. 392.

[3] *Trans. Roy. Soc. Edin.* vii. p. 86.

[4] Mr. J. M. Wilson has calculated that, if a tract of the earth's surface, 345 miles in breadth, be depressed one mile, it will undergo compression to the extent of 121 yards; at two miles the compression will be 189 yards; at eight miles 598 yards (*Geol. Mag.* v. p. 206). The observed amount of compression in districts of contorted rocks, however, far exceeds these figures.

[5] "Report, Devon and Cornwall," p. 187.

He computes the horizontal compression of the whole chain at 120,000 mètres, that is to say, that two points on the opposite sides of the chain have, by the folding of the crust that produced the Alps, been brought 120,000 mètres, or 74 miles, nearer each other than they were before the movement.[1]

Though the sight of such colossal foldings of solid sheets of rock impresses us with the magnitude of the compression to which the crust of the earth has been subjected, it perhaps does not convey a more vivid picture of the extent of this compression than is afforded by the fact that even in the minuter and microscopic structure of the rocks intricate puckerings are visible (Fig. 19). So intense has been the pressure, that even the tiny flakes of mica and other minerals have been forced to arrange themselves in complex foldings.

On an inferior scale, local compression and contortion may be caused by the protrusion of eruptive rocks. The characters of plicated rocks as part of the framework of the terrestrial crust are given in Book IV. Part IV.

5. **Jointing and Dislocation.**—Almost all rocks are traversed by vertical or highly inclined divisional planes termed *joints* (Book IV. Part II.). These have been regarded as due in some way to contraction during consolidation. But their regularity and frequent persistence across materials of very varying texture suggest rather the effects of internal pressure and movement within the crust. In an ingenious series of experiments Daubrée has imitated joints and fractures by subjecting different substances to undulatory movement by torsion and by simple pressure, and he infers that they have been produced by analogous movements in the terrestrial crust.[2]

But in many cases the rupture of continuity has been attended with relative displacement of the sides, producing what is termed a *fault*. Daubrée also shows experimentally how faults may arise from the same movements as have caused joints and from bending of the rocks. Faults must be regarded as connected rather with the elevation than with the subsidence of ground. Instead of having to occupy a diminished diameter, rocks get more room by being pushed up, and as they cannot occupy the additional space by any elastic expansion of their mass, they can only accommodate themselves to the new position by a series of dislocations.[3] Some portions will be pushed up farther than others, and this will happen more particularly to those which have a broad base. These will rise more than those with narrow bottoms, or the latter will seem to sink relatively to the former. Each broad-bottomed segment will thus be bounded by two sides sloping towards the upper part of the block. This is found to be almost invariably the case in nature. A fault or dislocation is nearly always inclined from the vertical, and the side

[1] "Mechanismus der Gebirgsbildung," 1878, vol. ii. p. 213.
[2] *Géol. Expérim.* Part I. sect. ii. chap. ii.
[3] See J. M. Wilson, *Geol. Mag.* v. p. 206.

to which the inclination rises, and from which it "hades," is the upthrow side. The details of these features of geological structure are reserved for Book IV. Part VI.

Part II.—Epigene or Surface Action.

On the surface of the globe and by the operation of agents working there the chief amount of visible geological change is now effected. This branch of inquiry is not involved in the preliminary difficulty regarding the very nature of the agents which attends the investigation of plutonic action. On the contrary, the surface agents are carrying on their work under our very eyes. We can watch it in all its stages, measure its progress, and mark in many ways how well it represents similar changes which for long ages previously must have been effected by similar means. But in the systematic treatment of this subject a difficulty of another kind presents itself. While the operations to be discussed are numerous and often complex, they are so interwoven into one great network that any separation of them under different subdivisions is sure to be more or less artificial, and is apt to convey an erroneous impression. While, therefore, under the unavoidable necessity of making use of such a classification of subjects, we must bear always in mind that it is employed merely for convenience, and that in nature, superficial geological action must be viewed as a whole, since the work of each agent has close relations with that of the others, and is not properly intelligible unless this connection be kept in view.

The movements of the air; the evaporation from land and sea; the fall of rain, hail, and snow; the flow of rivers and glaciers; the tides, currents, and waves of the ocean; the growth and decay of organized existence, alike on land and in the depths of the sea;—in short, the whole circle of movement, which is continually in progress upon the surface of our planet, are the subjects now to be examined. It would be desirable to adopt some general term to embrace the whole of this range of inquiry. For this end the word e p i g e n e may be suggested as a convenient term, and antithetical to h y p o g e n e, or subterranean action.

The simplest arrangement of this part of Geological Dynamics will be into three sections:—

I. A i r.—The influence of the atmosphere in destroying and forming rocks.

II. W a t e r.—The geological functions of the circulation of water through the air and between sea and land, and the action of the sea.

III. L i f e.—The part taken by plants and animals in preserving, destroying, or originating geological formations.

The words destructive, reproductive, and conservative, employed in describing the operations of the epigene agents, do not necessarily

imply that anything useful to man is destroyed, reproduced, or preserved. On the contrary, the destructive action of the atmosphere may cover bare rock with rich soil, while its reproductive effects may bury fertile soil under sterile desert. Again, the conservative influence of vegetation has sometimes for centuries retained as barren morass what might otherwise have become rich meadow or luxuriant woodland. The terms, therefore, are used in a strictly geological sense, to denote the removal and re-deposition of material, and its agency in preserving what lies beneath it.

Section i.—Air.

The geological action of the atmosphere arises partly from its chemical composition and partly from its movements. The composition of the atmospheric envelope has been already discussed (p. 30), and further information will be found under the head of Rain. The movements of the atmosphere are due to variations in the distribution of pressure or density, the law being that air always moves spirally from where the pressure is high to where it is low. Atmospheric pressure is understood to be determined by two causes, temperature and aqueous vapour. Since warm air, being less dense than cold air, ascends, while the latter flows in to take its place, the unequal heating of the earth's surface, by causing upward currents from the warmed portions, produces horizontal currents from the surrounding cooler regions inwards to the central ascending mass of heated air. The familiar land and sea breezes offer a good example of this action. Again the density of the air lessens with increase of water-vapour. Hence moist air tends to rise as warmed air does, with a corresponding inflow of the drier and consequently heavier air from the surrounding tracts. Moist air, ascending and diminishing atmospheric pressure, as indicated by the fall of the barometer, rises into higher regions of the atmosphere, where it expands, cools, condenses into visible cloud and into showers that descend again to the earth.

Unequal and rapid heating of the air, or accumulation of aqueous vapour in the air, and possibly some other influences not yet properly understood, give rise to extreme disturbances of pressure, and consequently to storms and hurricanes. For instance, the barometer sometimes indicates in tropical storms a fall of an inch and a half in an hour, showing that somewhere about a twentieth part of the whole mass of atmosphere has in that short space of time been displaced over a certain area of the earth's surface. No such sudden change can occur without the most destructive tempest or tornado. In Britain the tenth of an inch of barometric fall in an hour is regarded as a large amount, such as only accompanies great storms.[1] The rate of movement of the air depends on the difference of barometric pressure between the regions from and to which it blows. Since much of the potency of the air as a geological agent depends on its rate of

[1] Buchan's *Meteorology*, p. 266.

motion, it is of interest to note the ascertained velocity and pressure of wind as expressed in the subjoined table:—

	Velocity in Miles per hour.	Pressure in Pounds per square foot.
Calm	0	0
Light breeze	14	1
Strong breeze	42	9
Strong gale	70	25
Hurricane	84	36

While the paramount importance of the atmosphere as the vehicle for the circulation of moisture over the globe, and consequently as powerfully influencing the distribution of climate and the growth of plants and animals, must be fully recognized by the geologist, he is specially called upon to consider the influence of the air in directly producing geological changes upon the surface of the land and in augmenting the geological work done by water.

§ 1. Geological work of the air on land.

Viewed in a broad way the air is engaged in the twofold task of promoting the disintegration of superficial rocks and in removing and redistributing the finer detritus. These two operations however are so intimately bound up with each other that they cannot be adequately understood unless considered in their mutual relations.

1. Destructive action.—Still dry air not subject to much range of temperature has probably little or no effect on minerals and rocks. The chemical action of the atmosphere takes place almost entirely through dissolved moisture. This subject is discussed in the section devoted to Rain. But sunlight produces remarkable changes on a few minerals. Some lose their colours (celestine, rose-quartz), others change it, as cerargyrite does from colourless to black, and realgar from red to orange-yellow. Some of these alterations may be explained by chemical modifications induced by such causes as the loss of organic matter and oxidation. Certain subaerial changes though not properly atmospheric may be most appropriately considered here.

Effects of lightning.—Hibbert has given an account of the disruption by lightning of a solid mass of rock 105 feet long, 10 feet broad, and in some places more than 4 feet high, in Fetlar, one of the Shetland Islands, about the middle of last century. The dislodged mass was in an instant torn from its bed and broken into three large and several lesser fragments. "One of these, 28 feet long, 17 feet broad, and 5 feet in thickness, was hurled across a high point of rock to a distance of 50 yards. Another broken mass, about 40 feet long, was thrown still further, but in the same direction and quite into the sea. There were also many lesser fragments scattered up and down."[1]

The more usual effect of lightning, however, is to produce in

[1] Hibbert's *Shetland Islands*, p. 389, quoting from the MS. of Rev. George Low.

loose sand or more compact rock, tubes termed *fulgurites*, which range up to 2½ inches in diameter. These descend vertically but sometimes obliquely from the surface, occasionally branch, and rapidly lessen in dimensions till they disappear. They are formed by the actual fusion of the particles of the soil or rock surrounding the pathway of the electric spark. They have been most frequently found in loose sand. Abich has observed examples of such tubular perforations with vitreous walls in the porous reddish-white trachyte at the summit of Little Ararat. A piece of the rock about a foot long may be obtained perforated all over with irregular tubes having an average diameter of 3 centimètres. Each of these is lined with a blackish green glass, due to the fusion of the rock by the passage of the electric spark through it. As the whole summit of the mountain, owing to its frequent storms, is drilled in this manner, it is evident that the action of lightning may considerably modify the structure of the superficial portions of any mass of rock exposed on lofty eminences to frequent thunderstorms. Humboldt collected fulgurites from a trachyte peak in Mexico, and in two of his specimens the fused mass of the walls has actually overflowed from the tubes on the surrounding surface.[1]

Effects of changes of temperature.—Of far wider geological importance are the effects that arise among rocks and soils from the alternate expansion and contraction caused by daily or seasonal changes of temperature. In countries with a great annual range of temperature considerable difficulty is sometimes experienced in selecting building materials liable to be little affected by rapid or extreme variations in temperature, which induce an alternate expansion and contraction that prevents the joints of masonry from remaining close and tight.[2] If the daily thermometric variations are large, the effects are frequently striking. In Western America, where the climate is remarkably dry and clear, the thermometer often gives a range of more than 80° in the twenty-four hours. Thus in the Yellowstone district, at a height of 9000 feet above the sea, the author found the temperature of rocks exposed to the sun at noon to be more than 90° Fahr., and the thermometer at night to sink below 20°. In the Sahara and other African regions, as well as in Central Asia, the daily range is even greater. This rapid nocturnal contraction produces a strain so great as to disintegrate rocks into sand, or cause them to crack or peel off in skins or irregular pieces. Dr. Livingstone found in Africa (12° S. lat., 34° E. long.) that surfaces of rock which during the day were

[1] G. Rose, *Z. Deutsch. Geol. Gesch.* xxv. p. 112.

[2] In the United States, with an annual thermometric range of more than 90° Fahr., this difficulty led to some experiments on the amount of expansion and contraction in different kinds of building stones, caused by variations of temperature. It was found that in fine-grained granite the rate of expansion was ·000004825 for every degree Fahr. of increment of heat; in white crystalline marble it was ·000005668; and in red sandstone ·000009532, or about twice as much as in granite. Totten in *Silliman Amer. Journ.* xxii. p. 136. See *ante*, p. 284.

heated up to 137° Fahr., cooled so rapidly by radiation at night that, unable to sustain the strain of contraction, they split and threw off sharp angular fragments from a few ounces to 100 or 200 lb. in weight.[1] In the plateau region of North America, though the climate is too dry to afford much scope for the operation of frost, this daily vicissitude of temperature produces results that quite rival those usually associated with the work of frost. Cliffs are slowly disintegrated, the surface of arid plains is loosened, and the fine débris is blown away by the wind.

Effects of wind.—The geological work directly due to the air itself is mainly performed by wind. A dried surface of rock or soil, when exposed to wind, has the finer disintegrated particles blown away as dust or sand. This process, which takes place familiarly before our eyes on every street and roadway, may be instructively observed over cultivated ground, as well as on tracts with which man has not interfered. It is most marked in arid climates. Many old fortifications in Northern China, for example, have been laid bare to the very foundations by the removal of the surrounding soil through long-continued action of wind.[2] In the dry plateaux of North America, too, though no human memorials serve there as measures, extensive denudation from the same cause is in progress.

Not merely does the wind blow away what has already been loosened and pulverized. The grains of dust and sand are themselves employed to rub down the surfaces over which they are driven. The nature and potency of the erosion done by sand grains in rapid motion is well illustrated by the artificial sand-blast, in which a spray of fine siliceous sand driven with great velocity is made to etch or engrave glass. The abrading and polishing effects of wind-blown sand have long been noticed on Egyptian monuments exposed to sand-drift from the Libyan desert. Similar effects have been observed on dry volcanic plains of barren sand and ashes, as on the island of Volcano.[3] On the sandy plains of Wyoming, Utah, and the adjacent Territories, surfaces even of such hard materials as calcedony are etched into furrows and wrinkles, acquiring at the same time a peculiar and characteristic polish. There, also, large blocks of sandstone or limestone which have fallen from an adjacent cliff are attacked, chiefly at their base, by the stratum of drifting sand, until by degrees they seem to stand on narrow pedestals. As these supports are reduced in diameter the blocks eventually tumble over, and a new basal erosion leads to a renewal of the same stages of waste.[4] Hollows on rock surfaces may also be noticed where grains of sand, or small pebbles kept in gyration by the wind, gradually erode the cavities in which they lie.

As the result of the protracted action of wind upon an area

[1] Livingstone's *Zambesi*, pp. 492, 516.
[2] Richthofen's *China*, Berlin, 1877, i. p. 97.
[3] Kayser, *Z. Deutsch. Geol. Ges.* xxvii. p. 966.
[4] See Gilbert in Wheeler's *Report of U.S. Geograph. Surv. W. of 100th Meridian*, iii. p. 82. Blake, *Union Pacific Railroad Report*, v. pp. 92, 230.

exposed at once to great drought and to rapid vicissitudes of temperature, a continuous lowering of the general level takes place. The great sandy wastes thus produced represent, however, only a portion of the disintegration. Vast quantities of the finer dust are borne away by the wind into other regions, where, as will be immediately pointed out, they tend to raise the general level. Again, a considerable amount of fine dust and sand, blown into the neighbouring rivers, is carried down in their waters. In inland areas of drainage, indeed, like that of Central Asia, this transport does not finally remove the river-borne sediment from the basin of evaporation, but tends to fill up the lakes. Where, however, as in North America, rivers cross from the desert areas to the sea, there must be a permanent removal of wind-swept detritus by these streams. In the arid plateaux drained by the Colorado and its tributaries, so great has been the subaerial denudation that a thickness of thousands of feet of horizontal strata has been removed from the surface of level plains thousands of square miles in extent. This denudation, the extent of which is attested by the remaining cliffs and "buttes" or outliers of the strata, appears to be in great measure due to the causes here discussed, augmented in some districts by the effects of occasional heavy storms of rain.

One further effect produced by air in violent motion may be seen where, in forest-covered tracts of temperate latitudes, trees are occasionally prostrated over considerable spaces. The surface drainage being thus obstructed by the fallen stems, marsh plants spring up, and eventually the site of the forest is occupied by a peat-moss. (Section iii., Life.)

2. **Reproductive action.**—Growth of Dust. The fine dust and sand resulting from the general superficial disintegration of rocks would, if left undisturbed, accumulate *in situ* as a layer that would serve to protect the still undecayed portions underneath. Such a layer, indeed, partially remains, but being liable to continual attack and removal, may be taken to represent, where it occurs, the excess of disintegration over removal. In the vast majority of cases, however, the superficial coating of loose material is not due merely to the direct action of the air, but in far greater degree to the work of rain aided by the co-operation of plants and animals. To the layer thus variously produced, the name of Soil is given. Its formation is described at p. 339.

That wind plays an effective part in the re-distribution of superficial detritus is demonstrated by every cloud of dust blown from desiccated ground. We only need to take into account the multiplying power of time, to realize how extensively the soil of a district may be replenished and heightened by the dust thus strewn over it century after century. Dust and sand intercepted by the leaves of plants gradually descend to the soil below or are washed down by rain, so that even a permanently grassy surface may be slowly and imperceptibly heightened in this way.

On the sites of ancient monuments and cities this reproductive action of the atmosphere can be most impressively seen and most easily measured. In Europe on sites still inhabited by an abundant population, the deep accumulations beneath which ancient ruins often lie, are doubtless mainly to be assigned to the successive destructions and rebuildings of generation after generation of occupants. But at Nineveh, Babylon, and many other eastern sites, mounds which have been practically untouched by man for many centuries consist of fine dust and sand gradually drifted by the wind round and over abandoned cities, and protected and augmented by the growth of vegetation.[1] In these arid lands the air is often laden with fine detritus, which drifts like snow round conspicuous objects and tends to bury them up in a dust-drift. In Central Asia, even when there is no wind, the air is often thick with fine dust, and a yellow sediment settles from it over everything. In Khotan an exceedingly fine dust sometimes so obscures the sun, that even at midday one cannot read large print without a lamp. This dust deposited on the soil heightens and fertilizes it, and is regarded by the inhabitants as a kind of manure, without which the ground would be barren.[2]

Loess.—In the course of long ages, the constant deposit of dust has in these Asiatic countries formed a massive accumulation which sweeps over the plateaux and rises to 6000 feet or more above the sea, and for wide spaces conceals all older formations. Richthofen describes it in China under the name of Loess, as a wholly unstratified formation of a yellowish calcareous clay, amounting sometimes to 1500 or possibly over 2000 feet in thickness, having a tendency to split by vertical joints, and to form, along valleys and ravines, ranges of precipitous cliffs sometimes 500 feet high. It is firm enough to be excavated into tiers of chambers and passages by a teeming population. It contains abundant remains of land-shells, bones of land animals, and relics of a terrestrial vegetation.[3] Richthofen distinguishes between the *land-loess* here described and *lake-loess*, where water has co-operated.

For atmospheric accumulations of this nature Trautschold has proposed the name *eluvium*. They originate *in situ*, or at least only by wind-drift, whereas *alluvium* requires the operation of water, and consists of materials brought from a greater or less distance.[4] For wind-formed deposits the term "æolian" is sometimes used.

Sand-hills or Dunes.—Winds blowing continuously upon sand drive it onward, and pile it into irregular heaps and ridges, called

[1] The rubbish which in the course of many centuries has accumulated above the foundations of the Assyrian buildings at Kouyunjik was found by Layard to be in some places twenty feet deep. It consisted partly of ruins, but mostly of fine sand and dust blown from off the plains and mixed with decayed vegetable matter. Layard, *Nineveh and its Remains*, 3rd edit. ii. p. 120. See also Richthofen's *China*, i. p. 97.

[2] Johnson's "Journey to Ilchi, the capital of Khotan," *Journ. Geog. Soc.* xxxvii. 1867, p. 1.

[3] Richthofen's *China*, i. cap. ii. T. W. Kingsmill (*Q. J. Geol. Soc.* xxvii. p. 376) advances the untenable theory that this loess is of marine origin.

[4] *Z. Deutsch. Geol. Ges.* xxxi. p. 578.

"dunes." This takes place more especially on windward coasts either of the sea or of large inland lakes, where sandy shores are exposed to the drying influence of solar heat and wind; but similar effects may be seen even in the heart of a continent, as in the sandy deserts of the Sahara, Arabia, and in the arid lands of Utah, Arizona, &c. The dunes travel in parallel, irregular, and often confluent ridges, their general direction being transverse to the prevalent course of the wind. Local wind-eddies cause many irregularities of form. In humid climates rain-water or the drainage of small brooks is sometimes arrested between the ridges to form pools (*étangs* of the French coasts), where formations of peat occasionally take place. On the coast of Gascony the sea for 100 miles is so barred by sand-dunes, that in all that distance only two outlets exist for the discharge of the drainage of the interior. As fast as one ridge is driven away from a beach another forms in its place, so that a series of huge sandy billows, as it were, is continually on the move from the sea margin towards the interior. A stream or river may temporarily arrest their progress, but eventually they push the obstacle aside or in front of them. In this way the river Adour, on the west coast of France, has had its mouth shifted two or three miles. Occasionally, as at the mouths of estuaries, the sand is blown across so as gradually to exclude the sea, and thus to aid the fluviatile deposits in adding to the breadth of the land. In Fig. 82 a stream (*e e*) is represented as crossing a plain (*a*)

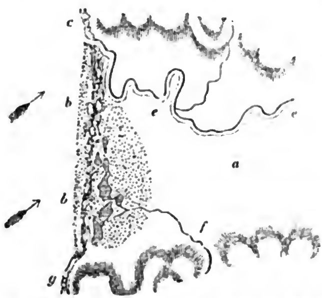

FIG. 82.—SAND-DUNES AFFECTING LAND-DRAINAGE (*B.*).

at the margin of the sea or of a large inland sheet of water, bounded by a range of sand-dunes (*b b*) extending between the two lines of cliff (*c g*). The stream has been turned to its right bank by the advance of the dunes driven by a prevalent wind blowing in the direction of the arrows. A brook (*f*) has been arrested among the sandy wastes, whence, after forming a few pools, it finds egress by soaking through the sandy barrier.

Perfect "ripple-marks" may often be observed on blown sand. The sand grains, pushed along by the wind, travel up the long slopes

and fall over the steep slopes. Not only do the particles travel, but the ridges also more slowly follow each other, as in Fig. 83.

The western sea-board of Europe, exposed to prevalent westerly and south-westerly winds, affords many instructive examples of these æolian or wind-formed deposits. The coast of Norfolk is fringed with sand-hills fifty to sixty feet high. On parts of the coast of Cornwall,[1] the sand consists mainly of fragments of shells and corallines, and through the action of rain becomes sometimes

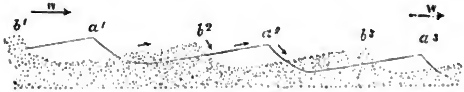

Fig. 83.—Diagram of Ripples in blown Sand. The ridges b^1, b^2, b^3, impelled in the direction W W, successively come to occupy the Hollows a^1, a^2, a^3 (*B.*).

cemented by carbonate of lime (or oxide of iron) into a stone so compact as to be fit for building purposes. Long tracts of blown sand are likewise found on the Scottish and Irish[2] coast-lines. Sand-dunes extend for many leagues along the French coast, and thence, by Flanders and Holland, round to the shores of Courland and Pomerania. On the coast of Holland they are sometimes, though rarely, 260 feet high,—a common average height being 50 to 60 feet.[3]

The breadth of this maritime belt of sand varies considerably. On the east coast of Scotland it ranges from a few yards to three miles; on the opposite side of the North Sea it attains on the Dutch coast sometimes to as much as five miles. The rate of progress of the dunes towards the interior depends upon the wind, the direction of the coast, and the nature of the ground over which they have to move. On the low and exposed shores of the Bay of Biscay, when not fixed by vegetation, they travel inland at a rate of about 16½ feet per annum, in Denmark at from 3 to 24 feet. In the course of their march they envelop houses and fields; even whole parishes and districts once populous have been overwhelmed by them.[4]

Along the margins of large lakes and inland seas many of the phenomena of an exposed sea-coast are repeated on a scarcely inferior scale. Among these must be included sand-dunes, such as those which, reaching heights of 100 to 200 feet on the south-eastern shores of Lake Michigan, have entombed forests, the tops of the trees being still visible above the drifting sand. Large dunes occur also on the eastern borders of the Caspian Sea, where the sand

[1] Ussher, *Geol. Mag.* (2), vi. p. 307, and authorities there cited.

[2] See Kinahan, *Geol. Mag.* viii. p. 155.

[3] On the growth of Holland through the operation of the wind and the sea, see Élie de Beaumont, "Leçons de Géologie pratique," i.

[4] This destruction has been, during the last quarter of a century, averted to a great extent by the planting of pine forests, the turpentine of which has become the source of a large revenue.

spreads over the desert region between that sea and the Sea of Aral, into which latter sheet of water the spread of the sand has driven the course of the Oxus, once a tributary of the Caspian.

In the interior of continents the existence of vast arid wastes of loose sand, situated far inland and remote from any sheet of fresh water, suggests curious problems in physical geography. In some instances these tracts have been at a comparatively recent geological period covered by the sea. The desert of the Sahara is no doubt in great part a modern sea bottom which has been upraised and dried, for shells of the common cockle (*Cardium edule*) are found lying on the surface up to heights of 900 feet above the level of the Mediterranean. Yet the disintegration of rock in these torrid and rainless regions must be great (*ante*, p. 319), so that the existing sand may be partly of subaerial origin. In other dry climates it is quite certain that the sand-wastes are entirely of this latter character. The sandy deserts of the high plateaux of western North America, which have never been under the sea for a long series of geological ages, show, as we have already found (p. 320), the mode and progress of their formation from atmospheric disintegration alone. In Asia lie the vast deserts of Gobi;[1] to the east of the Red Sea stretch the great sand-wastes of Arabia; and to the west those of Libya. In the south-east of Europe, over the steppes of Southern Russia and the adjacent territories, wide areas of sandy desert occur. Captain Sturt found vast deserts of sand in the interior of Australia, with long bands of dunes 200 feet high, united at the base and stretching in straight lines as far as the eye could reach.[2]

Dust-showers, Blood-rain.—Besides the universal transport and deposit of dust and sand already described, a phenomenon of a more aggravated nature is observed in tropical countries, where great droughts are succeeded by violent hurricanes. The dust or sand of deserts and of dried lakes or river-beds is then sometimes borne away into the upper regions of the atmosphere, where, meeting with strong aerial currents which transport it for hundreds and even thousands of miles, it descends again to the surface, in the form of "red-fog," "sea-dust," or "sirocco-dust." This transported material, usually of a brick-dust or cinnamon colour, is occasionally so abundant as to darken the air and obscure the sun, and to cover the decks, sails, and rigging of vessels which may even be hundreds of miles from

[1] For important information regarding the Central Asiatic wastes, see Richthofen's "China," i.

[2] For accounts of sand-dunes, their extent, progress, structure, and the means employed to arrest their progress, the student may consult Andersen's "Klitformationen," 1 vol. 8vo. Copenhagen, 1861; Laval in *Annales des Ponts et Chaussées*, 1847, 2me sem.; Marsh's "Man and Nature," 1864, and the works cited by him. Forchhammer, *Edin. New Phil. Journ.* xxxi. (1841), p. 61. Élie de Beaumont, "Leçons de Géologie pratique," vol. i. p. 183. Information regarding the sands of the interior of continents will be found in Palgrave's "Travels in Arabia." Blake in *Union Pacific Railroad Report*, v. Tristram, "The Great Sahara," 1860. Desor, "Le Sahara, ses différents types de déserts." *Bull. Soc. Sci. Nat. Neufchâtel*, 1864. Richthofen's "China," i.

land. Rain falling through such a dust-cloud mixes with it, and descends either on sea or land as what is popularly called "blood-rain." This is frequent on the north-west of Africa, about the Cape Verd Islands, in the Mediterranean, and over the bordering countries. A microscopic examination of this dust by Ehrenberg led him to the belief that it contains numerous diatoms of South American species; and he inferred that a dust-cloud must be swimming in the atmosphere, carried forward by continuous currents of air in the region of the trade-winds and anti-trades, but suffering partial and periodical deviations. But much of the dust seems to come from the sandy plains and desiccated pools of the north of Africa. Daubrée recognized in 1865 some of the Sahara sand which fell in the Canary Islands. On the coast of Italy a film of sandy clay, identical with that from parts of the Libyan desert, is occasionally found on windows after rain. In the middle of last century an area of Northern Italy, estimated at about 200 square leagues, was covered with a layer of dust which in some places reached a depth of one inch. In 1846 the Sahara dust reached as far as Lyons. Should the travelling dust encounter a cooler temperature, it may be brought to the ground by snow, as has happened in the north of Italy, and more notably in the east and south-east of Russia, where the snows are sometimes rendered dirty by the dust raised by winds on the Caspian steppes. It is easy to see that a prolonged continuance of this action must give rise to widespread deposits of dust, mingled with the soil of the land, and with the silt and sand of lakes, rivers, and the sea; and that the minuter organisms of tropical regions may thus come to be preserved in the same formations with the terrestrial or marine organisms of temperate latitudes.[1]

The transport of volcanic dust by wind, already (p. 219) referred to, may be again cited here as another example of the geological work of the atmosphere. Thus from the Icelandic eruptions of 1874–75 vast showers of fine ashes not only fell on Iceland to a depth of six inches, destroying the pastures, but were borne over the sea and across Scandinavia to the east coast of Sweden. Considerable deposits of volcanic material may thus in the course of time be formed even far remote from any active volcano.[2]

Transportation of Seeds.—Besides the transport of dust and minute organisms for distances of many thousands of miles, wind may also transport living seeds, which, finally reaching a congenial climate and soil, may take root and spread. We are yet, however, very ignorant as to the extent to which this cause has actually operated in the establishment of any given local flora. With regard to the minute forms of vegetable life, indeed, there can be no doubt as to the efficacy of the wind to transport them across vast distances on

[1] See Humboldt on dust whirlwinds of Orinoco, "Aspects of Nature;" also Maury, "Phys. Geog. of Sea," chap. vi.; Ehrenberg's "Passat-Staub und Blut-Regen," *Berlin Akad.* 1847. A paper by A. von Lasaulx on so-called cosmic dust has just appeared in Tschermak's *Mineral. Mittheil.* 1880, p. 517.

[2] Nordenskiöld, *Geol. Mag.* (2), iii. p. 292.

the surface of the globe. Upwards of 300 species of diatoms have been found in the deposits left by dust-showers. Among the millions of organisms thus transported it is hardly conceivable that some should not fall into a fitting locality for their continued existence and the perpetuation of their species. Animal forms of life are likewise diffused through the agency of winds. Insects and birds are often met with at sea many miles distant from the land from which they have been blown. Such organisms are in this way introduced into oceanic islands, as is well shown in the case of Bermuda. Hurricanes, by which large quantities of water are sucked up from lakes and rivers over which they pass, may also transport part of the fauna of these waters to other localities.

Efflorescence products.—Among the formations due in large measure to atmospheric action must be included the saline efflorescences which form upon the ground in the dry interior basins of continents. The steppes of Southern Russia, and the plains round the Great Salt Lake of Utah, may be taken as illustrative examples. Water rising by capillary attraction through the soil to the surface is there evaporated, leaving behind a white crust, by which the upper portion of the soil is covered and permeated. The incrustations consist of sodium chloride, sodium and calcium carbonates, calcium, sodium, and potassium sulphates in various proportions, these being the salts present also in the salt lakes of the same regions (p. 398).[1]

§ 2. Influence of the Air on Water.

The results of the action of the air upon water will be more fitly noticed in the section devoted to Water. It will be enough to notice here—

1. Ocean currents.—These are mainly dependent for their existence and direction on the circulation of the atmosphere. The in-streaming of air from cooler latitudes towards the equator causes a drift of the sea-water in the same direction. As, owing to the rotation of the earth, these aerial currents tend to take a more and more westerly trend in approaching the equator, they communicate this trend to the marine currents, which, likewise moving into regions with a greater velocity of rotation than their own, are all the more impelled in the same westerly direction. Hence the dominant equatorial current, which flows westward across the great ocean. Owing, however, to the position of the continents across its path, this great current cannot move uninterruptedly round the earth. It is split into branches which turn to right and left, and, bathing the shores of the land, carry some of the warmth of the tropics into more temperate latitudes. Return currents are thus generated from cooler latitudes towards the equator. (Section ii. § 6.)

2. Waves.—The impulse of the wind upon a surface of water throws that surface into pulsations which range in size from mere

[1] On efflorescence of Great Salt Lake region, see *Exploration of 40th Parallel*, i. sect. v. Consult also E. Tietze, "Entstehung der Salzsteppen," *Jahrb. Geol. Reichsanst.* 1877.

ripples to huge billows. Long-continued gales from the seaward upon an exposed coast indirectly effect much destruction, by the formidable battery of billows which they bring to bear upon the land. Wave-action is likewise seen in a marked manner when wind blows strongly across a broad inland sheet of water, such as Lake Superior. (Section ii. § 6.)

3. Alteration of the Water-level.—When the wind blows freshly for a time across a limited area of water, it drives the water before it, which is thus kept temporarily at a higher level, at the further or windward side. In a tidal sea, such as that which surrounds Great Britain, and which sends abundant long arms into the land, a high tide and a gale are sometimes synchronous. This conjunction causes the high tide to rise to a greater height than elsewhere in those bays or firths which look windward. With this conjunction of wind and tide, considerable damage to property has sometimes been done by the flooding of warehouses and stores, while even a sensible destruction of cliffs and sweeping away of loose materials may be chronicled by the geologist. On the other hand, a wind from the opposite quarter coincident with an ebb tide will drive the water out of the inlet, and thus make the water-level lower than it should otherwise be. But even in inland seas where tides are small or imperceptible, considerable oscillations of water-level may arise from this action of the wind. At Naples for example a long-continued south-west wind raises the level of the water several inches. In long fresh-water lakes also similar results attend prolonged gales along the length of the lakes.

Section ii.—Water.

Of all the terrestrial agents by which the surface of the earth is geologically modified, by far the most important is water. We have already seen, when following hypogene changes, how large a share is taken by water in the phenomena of volcanoes and in other subterranean processes. Returning to the surface of the earth and watching the operations of the atmosphere, we soon learn how important a part of these is sustained by the aqueous vapour by which the atmosphere is pervaded.

The substance which we term water exists on the earth in three well-known forms—(1) gaseous, as invisible vapour; (2) liquid, as water; and (3) solid, as ice. The gaseous form has already been noticed as one of the characteristic ingredients of the atmosphere (p. 31). Apart from the heated reservoirs at the roots of volcanoes, it is in the air that this condition of the water-substance prevails. By the sun's heat vast quantities of vapour are continually raised from the surface of the seas, rivers, lakes, snow-fields, and glaciers of the world. This vapour remains invisible until the air containing it is cooled down below its dew-point, or point of saturation,—a result which follows upon the union or collision of two aerial currents of different temperatures, or the rise of the air into the upper cold

regions of the atmosphere, where it is chilled by expansion, by radiation, and by contact with cold mountains. According to recent researches, condensation appears only to take place on free surfaces, and the formation of cloud and mist is explained by condensation upon the fine microscopic dust of which the atmosphere is full.[1] At first minute particles of water vapour appear, which either remain in the liquid condition, or, if the temperature is sufficiently low, are at once frozen into ice. As these changes take place over considerable spaces of the sky, they give rise to the phenomena of clouds. Further condensation augments the size of the cloud-particles, and at last they fall to the surface of the earth, if still liquid, as rain; if solid, as snow or hail; and if partly solid and partly liquid, as sleet. As the vapour is largely raised from the ocean surface, so in great measure it falls back again directly into the ocean. A considerable proportion, however, descends upon the land, and it is this part of the condensed vapour which we have now to follow. Upon the higher elevations it falls as snow, and gathers there into snow-fields, which, by means of glaciers, send their drainage towards the valleys and plains. Elsewhere it falls chiefly as rain, some of which sinks underground to gush forth again in springs, while the rest pours down the slopes of the land, feeding brooks and torrents, which, swollen further by springs, gather into broader and yet broader rivers, whereby the accumulated drainage of the land is carried out to sea. Thence once more the vapour rises, to reappear in clouds and rain and to feed the innumerable water-channels by which the land is furrowed from mountain-top to sea-shore.

In this vast system of circulation, ceaselessly renewed, there is not a drop of water that is not busy with its allotted task of changing the face of the earth. When the vapour ascends into the air it is comparatively speaking chemically pure. But when, after being condensed into visible form, and working its way over or under the surface of the land, it once more enters the sea, it is no longer pure, but more or less loaded with material taken by it out of the air, rocks, or soils through which it has travelled. Day by day the process is advancing. So far as we can tell, it has never ceased since the first shower of rain fell upon the earth. We may well believe, therefore, that it must have worked marvels upon the surface of our planet in past time, and that it may effect vast transformations in the future. As a foundation for such a belief let us now inquire what it can be proved to be doing at the present time.

§ 1. Rain.

Rain effects two kinds of changes upon the surface of the land. (1.) It acts *chemically* upon soils and stones, and sinking under ground continues, as we shall find, a great series of similar reactions

[1] Coulier and Mascart, *Naturforscher* 1875, p. 400. Aitken, *Proc. Roy. Soc. Edin.* December 1880.

there. (2.) It acts *mechanically*, by washing away loose materials, and thus powerfully affecting the contours of the land.

1. **Chemical Action.**—This depends mainly upon the nature and proportion of the substances abstracted by rain from the air in its descent to the earth. Rain absorbs a little air, which always contains carbonic acid as well as other ingredients, in addition to its nitrogen and oxygen (p. 31). Rain thus washes the air and takes impurities out of it, by means of which it is enabled to work many chemical changes that it could not accomplish were it to reach the ground as pure water.

Composition of Rain-water.—Numerous analyses of rain-water show that it contains in solution about 25 cubic centimetres of gases per litre.[1] An average proportional percentage is by measure —nitrogen, 64·47; oxygen, 33·76; carbonic acid, 1·77. Carbonic acid being more soluble than the other gases is contained in rain-water in proportions between 30 and 40 times greater than in the atmosphere. Oxygen too is more soluble than nitrogen. This difference acquires a considerable importance in the chemical operations of rain. Other substances are present in smaller quantities. In England there is an average of 3·95 parts of solid impurity in 100,000 parts of rain.[2] Nitric acid sometimes occurs in marked proportions: at Bâle it was found to reach a maximum of 13·6 parts in a million, with 20·1 parts of nitrate of ammonia. Sulphuric acid likewise occurs especially in the rain of towns and manufacturing districts.[3] Sulphates of the alkalies and alkaline earths have been detected in rain. But the most abundant salt is chloride of sodium, which appears in marked proportions on coasts, as well as in the rain of towns and industrial districts. Rain taken at the Land's End in Cornwall during a strong south-west wind was found to contain 2·180 of chlorine, or 3·591 parts of common salt in every 10,000 of rain. The mean proportion of chlorine over England is about 0·022 in every 10,000 parts of rain; at Ootacamund 0·003 to 0·004.[4]

In washing the air rain carries down also inorganic particles or motes floating there; likewise organic dust and living germs.[5] As the result of this process the soil comes to be not merely watered but

[1] Baumert, *Ann. Chem. Pharm.* lxxxviii. p. 17. The proportion of carbonic acid found by Peligot was 2·4. See also Bunsen, *op. cit.* xciii. p. 20. Roth, *Chem. Geol.* i. p. 44. Dr. Angus Smith's *Air and Rain*, 1872, p. 225.

[2] *Rivers Pollution Commission*, 6th Rep. p. 29.

[3] The occurrence of sulphuric and nitric acids in the air, especially noticeable in large towns, leads to considerable corrosion of metallic surfaces, as well as of stones and lime. The mortar of walls may often be observed to be slowly swelling out and dropping off, owing to the conversion of the lime into sulphate. Great injury is likewise done from a similar cause to marble monuments in exposed graveyards. See Dr. Angus Smith, *op. cit.* p. 444. Geikie, *Proc. Roy. Soc. Edin.* 1879–80, p. 518.

[4] Dr. Angus Smith, *op. cit.* *Rivers Pollution Commission*, 6th Rep. 1874, p. 425.

[5] Among the inorganic contents of rain and snow fine dust and spherules of iron, probably in part of cosmic origin, have been specially noted. *See* Jung, *Bull. Soc. Vaudoise Sci. Nat.* xiv. p. 493, authorities cited *ante* p. 64; Von Lasaulx, as cited on p. 326. The organic matter is revealed by the putrid smell which long-kept rain-water gives out.

fertilized by the rain. Dr. Angus Smith cites the experience of M. J. J. Pierre, who found by analysis that in the neighbourhood of Caen, in France, a hectare of land receives annually from the atmosphere by means of rain—[1]

Chloride of sodium	37·5	kilogrammes.
" potassium	8·2	"
" magnesium	2·5	"
" calcium	1·8	"
Sulphate of soda	8·4	"
" potash	8·0	"
" lime	6·2	"
" magnesia	5·9	"

Not only rain but also dew and hoar-frost abstract impurities from the atmosphere. The analyses performed by the Rivers Pollution Commission show that dew and hoar-frost condensing from the lower and more impure layers of the air are even more contaminated than rain, as they contain on an average in England 4·87 parts of solid impurity in 100,000 parts, with ·198 of ammonia.[2]

It is manifest that rain reaches the surface by no means chemically pure water, but having absorbed from the air various ingredients which enable it to accomplish a suite of chemical changes upon rocks and soils. So far as we know at present, the three ingredients which are chiefly effective in these operations are oxygen, carbonic acid, and organic matter. As soon as it touches the earth, however, rain begins to absorb additional impurities, notably increasing its proportion of carbonic acid and of organic matter, which it obtains from decomposing animal and vegetable matter. Among the organic products most efficaceous in promoting the corrosion of minerals and rocks are the so-called ulmic or humous substances that form soluble compounds with alkalies and alkaline earths, which are eventually converted into carbonates.[3] Hence as rain-water, already armed with gases absorbed from the atmosphere, proceeds to take up these organic acids from the soil, it is endowed with considerable chemical activity even at the very beginning of its geological career.

Chemical and mineralogical changes due to rain-water.—In previous pages it was pointed out that all rocks and minerals are in varying degrees porous and permeable by water, that probably no known substance can under all conditions resist solution in water, and that the subsequent solvent power of water is greatly increased by the solutions which it effects and carries with it in its progress through rocks (pp. 298, 302). The chemical work done by rain may be conveniently considered under the four heads of Oxidation, Deoxidation, Solution, and Hydration.

1. *Oxidation.*—The prominence of oxygen in rain-water, and its

[1] Angus Smith, *op. cit.* p. 233. [2] *Rivers Pollution Commission*, 6th Rep. p. 32.
[3] Senft, *Z. Deutsch. Geol. Ges.* xxiii. p. 665, xxvi. p. 954. This subject has recently been well treated in a paper by A. A. Julien "On the geological action of the humus acids" (*Proc. Amer. Assoc.* xxviii. 1879, p. 311), to which further reference is made in later pages.

readiness to unite with any substance that can contain more of it, render oxidation a marked feature of the passage of rain over rocks. A thin oxidized pellicle is formed on the surface, and this, if not at once washed off, is thickened from inside until a crust is formed over the stone. This process is simply a rusting of those ingredients which, like metallic iron, have no oxygen, or have not their full complement of it. The ferrous and manganous oxides so frequently found as constituents of minerals are specially liable to this change. In hornblende and augite, for example, one cause of weathering is the absorption of oxygen by the iron and the hydration of the resultant peroxide. Hence the yellow and brown sand into which rocks abounding in these minerals are apt to weather.

2. *Deoxidation.*—Rain becomes a reducing agent by absorbing from the atmosphere and soil organic matter which, having an affinity for oxygen, decomposes peroxides and reduces them to protoxides. This change is especially noticeable among iron oxides, as in the familiar white spots and veinings so common among red sandstones. These rocks are stained red by ferric oxide (hematite), which, reduced by decaying organic matter to ferrous oxide, is usually removed in solution as an organic salt or carbonate. When the deoxidation takes place round a fragment of plant or animal, it usually extends as a circular spot; where water containing the organic matter permeates along a joint or other divisional plane, the decoloration follows that line. Another common effect of the presence of organic matter is the reduction of sulphates to the state of sulphides. Gypsum is thus decomposed into sulphide of calcium, which in water readily gives calcium carbonate and sulphuretted hydrogen, and the latter by oxidation leaves a deposit of sulphur. Hence from original beds of gypsum, layers of limestone and sulphur have been formed, as in Sicily and elsewhere (p. 64).[1]

3. *Solution.*—A few minerals (halite, for example) are readily soluble in water without chemical change, and without the aid of any intermediate element. In the great majority of cases, however, the solution is effected through the medium of carbonic acid or other re-agent. A familiar illustration is the solution and removal of lime from the mortar of a bridge or vault, and the deposit of the material so removed in stalactites and stalagmites (p. 112). Another common example is seen in the rapid effacement of marble epitaphs in our churchyards. It has lately been shown that in the atmosphere of a large town with abundant coal-smoke and rain, inscriptions on marble become illegible in half a century. Pfaff recently determined that a slab of Solenhofen limestone 2520 square millimetres in superficies lost in two years by the solvent action of rain 0·180 gramme in weight, in three years 0·548, the original polish being replaced by a dull earthy surface on which fine cracks and incipient exfoliation began to appear. Taking the specific gravity of the stone at 2·6, the yearly loss of surface amounts to $\frac{1}{74\cdot5}$

[1] The reducing action of organic acids is further described in Section iii.

millimetre, so that a crag of such limestone would be lowered 1 metre in 72,000 years by the solvent action of rain.[1]

Not only carbonates but silicates of lime, potash, and soda, combinations existing abundantly as constituents of rocks, are attacked by rain-water; their silica is liberated and partly dissolved, while their alkalies or alkaline earths, becoming carbonates, are removed in solution. The felspars for example are thus decomposed, the alkalies and the lime being gradually abstracted together with a portion of the silica. The result is a slow disintegration of the stone into sand and clay.

4. *Hydration.*—Some anhydrous minerals, when exposed to the action of the atmosphere, absorb water (become hydrous), and may then be more prone to further change. Anhydrite becomes by addition of water, gypsum, the change being accompanied by an increase of bulk. It has been suggested that local uplifts of the ground may sometimes have been caused by the hydration of large subterranean beds of anhydrite. Many substances on oxidizing likewise become hydrous. The oxidation of ferrous oxide in damp air gives rise to hydrous ferric oxide, with its characteristic yellow and brown colours on weathered surfaces.

Weathering.—This term expresses the general result of all kinds of meteoric action upon the superficial parts of rocks. As these changes almost invariably lead to disintegration of the surface, the word weathering has come to be naturally associated in the mind with a loosened crumbling condition of stone. But the influence of the atmospheric agents is not invariably to destroy the coherence of the integral particles of rocks. In some cases stones harden on exposure. Certain sandy rocks, for example, like the "grey weathers" and scattered Tertiary blocks in the Ardennes, become under meteoric influence a kind of lustrous quartzite. In other cases there may be more complex molecular rearrangements, such as those remarkable transformations to which Brewster first called attention in the case of artificial glass.[2] He showed that in thin films of decomposed glass obtained from Nineveh and other ancient sites, concentric agate-like rings of devitrification are formed round isolated points, closely analogous to those above described as artificially produced by the action of heated alkaline waters (p. 301), and that groups of crystals or crystallites, "probably of silex," are developed from many independent points in the decomposing layer. Coloured films indicative of incipient decomposition have been observed on surfaces of glass exposed only to the air of the atmosphere for twenty or thirty years. Brilliantly iridescent films have been produced on the glass of windows exposed for not more than twenty years to the air and ammoniacal vapours of a stable.[3] That

[1] Pfaff, *Z. Deutsch. Geol. Ges.* xxiv. p. 405, and "Allgemeine Geologie als exacte Wissenschaft," p. 317. Roth, *Chem. Geol.* i. p. 70. Geikie, *Proc. Roy. Soc. Edin.* x. 1879–80, p. 518.

[2] *Trans. Roy. Soc. Edin.*, xxii. 607, xxiii. 193.

[3] This fact has been observed by my friend Mr. P. Dudgeon of Cargen in an ill-ventilated cow-house, and I have seen the plates of glass removed from the windows.

similar transformations take place in the natural silicates of rocks seems in the highest degree probable. They may form the earliest stages of the change to the usual opaque earthy decomposing crust, in which, of course, all trace of any structure developed in the preliminary weathering is lost.

In humid and temperate climates weathering is mainly due to the solvent influence of rain; in high mountainous situations, as well as in lower regions where the temperature falls below the freezing point in winter, it is largely produced by the action of frost, to be afterwards described; in arid lands subject to great and rapid alterations of temperature it is caused by the strain of alternate expansion and contraction and the mechanical action of the wind (p. 319). As the name denotes, weathering is dependent on meteorological conditions, and varies even in the same rock as these condi-

Fig. 84.—Weathered Sandstone Cliffs showing irregular Honeycombing and Weathering along Planes of Stratification (*B.*).

tions change, but is likewise almost infinitely diversified according to the structure, texture, and composition of rocks.

Mere hardness or softness forms no sure index to the comparative power of a rock to resist weathering. Many granites, for instance, weather to clay deep into their mass, while much softer limestones retain smooth hard surfaces. Nor is the depth of the weathered surface any better guide to the relative rapidity of waste. A tolerably pure limestone may weather with little or no crust, and yet may be continually losing an appreciable portion of its surface by solution, while an igneous rock like a dolerite or basalt may have a thick decomposed crust and yet weather with extreme slowness. In the former case, the substance of the rock being removed in solution, few or no insoluble portions are left to mark the progress of decay, while in the igneous rock the removal of but a comparatively small proportion causes the disintegration of the rock,

and the remaining soluble parts are found as a crumbling crust. Impure limestone, however, yields a weathered crust of more or less insoluble particles. Hence, as we have already seen, the relative purity of limestones may be roughly determined by comparing their weathered surfaces, where, if they contain much sand, the grains will be seen projecting from the calcareous matrix; should the rock be very ferruginous, the yellow hydrous peroxide or ochre will be found as a powdery crust, or if the rock be fossiliferous, the weathered surface will commonly present the fossils standing out in relief. An experienced fossil collector will always search well these weathered limestones, for he often finds there, delicately picked out by the weather, minute and frail fossils which are wholly invisible on a freshly broken surface of the stone. This difference arises from the greater insolubility of the crystalline calcite composing the organic remains than of the more granular calcite in which they are imbedded.

Rocks liable to little chemical change are best fitted to resist weathering, provided their particles have sufficient cohesion to withstand the mechanical processes of disintegration. Siliceous sandstones offer excellent examples of this permanence. Consisting mainly of the durable mineral quartz, they are sometimes able so to withstand decay that buildings made of them still retain, after the lapse of centuries, the chisel-marks of the builders. Many sandstones, however, contain argillaceous, calcareous, or ferruginous concretions which weather more rapidly than the rock, and cause it to assume a honeycombed surface; others are full of a diffused cement (clay, lime, iron), the decay of which causes the rock to crumble down into sand. In sandstones, as indeed in most stratified rocks, there is a tendency towards more rapid weathering along the planes of stratification, so that the stratified structure is brought out very clearly on natural cliffs (Fig. 84). In many ferruginous sandstones and clay ironstones successive yellow or brown zones or shells may be traced inward from the surface, frequently due to changes of the ferrous carbonate into limonite, the interior remaining still fresh. In many prismatic massive rocks (basalt, diorite, &c.) segments of the prisms weather into spheroids, in which successive weathered rings form crusts like the concentric coats of an onion (Figs. 85, 86). Where one of these rocks has been intruded as a dyke, it sometimes decomposes to a considerable depth into a mass of brown ferruginous balls in a surrounding sandy matrix—the whole having at first a resemblance to a conglomerate made of rolled and transported fragments (Fig. 87).

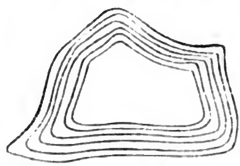

FIG. 85.—RINGS OF WEATHERING.

No rock presents greater variety of weathering than granite. Some remarkably durable kinds only yield slowly at the edges of

the joints, the separated masses gradually assuming the form of rounded blocks like water-worn boulders. Other kinds decompose

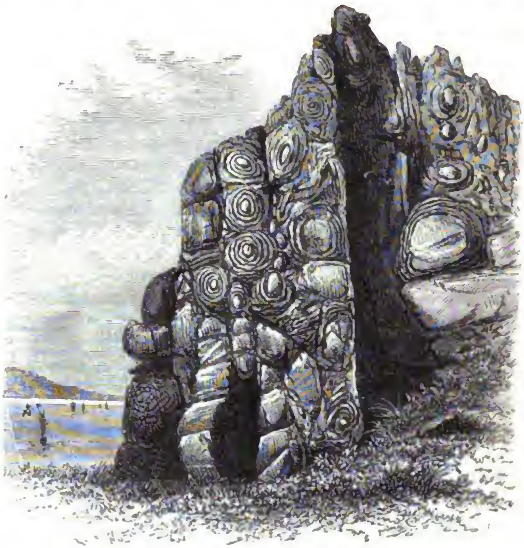

Fig. 86.—Spheroidal Weathering of Dolerite, North Queensferry.

to a depth of 30 or 40 feet, and can be dug out with a spade, as in Cornwall and Devon, where the kaolin from the rotted granite is largely extracted for pottery purposes. That what appears to be mere loose sand and clay is really rock decomposed *in situ*, is proved

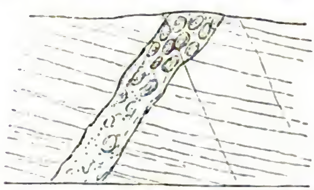

Fig. 87.—Basalt Dyke Weathering into Spheroids.

by the quartz veins which ascend from the solid rock (*a* Fig. 88) into the friable part (*b*), and by the entire agreement in structure between the two portions. Here and there kernels of still undecomposed

granite may be seen (as at *c c* in Fig. 89), surrounded by thoroughly decayed material, and, like the solid cores of basalt, above mentioned, presenting a deceptive resemblance to some accumulation of trans-

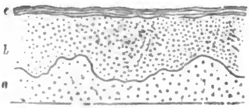

FIG. 88.—DECOMPOSITION OF GRANITE. *a*, Solid granite; *b*, decomposed granite; *c*, vegetable soil.

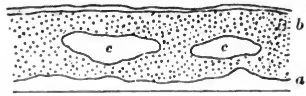

FIG. 89.—DECOMPOSITION OF GRANITE. *a*, solid granite; *b*, decomposed granite; *c c*, kernels of still undecomposed granite.

ported materials. Owing to its numerous joints, granite occasionally weathers into forms that resemble ruined walls. Large slabs, each defined by joint planes, weather out one above another like tiers of masonry (Fig. 90). As these become surrounded and loosened by disintegration they slip off and expose lower parts of the rock to the same influences. Here and there a separate block becomes so poised that it may be readily moved to and fro by the hand, as in the so-called "rocking-stones" of granitic districts. The disintegration being likewise liable to considerable local differences, some portions of the

FIG. 90.—WEATHERING OF GRANITE ALONG ITS JOINTS (*B.*).

blocks are weathered into cavities often with a singularly artificial appearance, as in the "rock basins" of the south-west of England (Fig. 91).

To the influence of weathering many of the most familiar minor contours of the land may be traced. So characteristic are these forms for particular kinds of rock, that they serve as a means of recognizing them even from a distance. (Book VII.)

In countries which have not been under water for a vast lapse of time, and where consequently the superficial rocks have been continuously exposed to subaerial disintegration, thick accumulations of "rotted rock" are found on the surface. The extent of this change is sometimes impressively marked in areas of calcareous rocks. Limestone being mostly soluble, its surface is continually dissolved by rain, while the insoluble portions remain behind as a slowly increasing deposit. In regions which, possessing the necessary conditions of climate, have been for a long period unsubmerged, tracts of limestone, unprotected by glacial or other accumulations, are found to be covered particularly with a red loam or earth. This character-

istic layer occurs on a limited scale over the chalk of the south-east of England, where, with its abundant flints, it lies as the undissolved ferruginous residue of the chalk that has been removed to a depth of many yards. It occurs likewise in swallow-holes and other passages dissolved out of calcareous masses, and forms the well-known red-earth of bone caves. In south-eastern Europe it plays an important

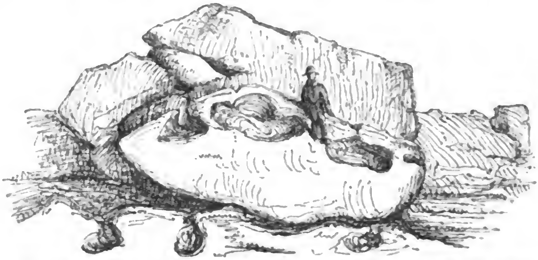

Fig. 91.—The "Kettle and Pans," St. Mary, Scilly, Cavities weathered out of Granite (*B.*).

part among superficial deposits, being extensively developed over the limestone districts, especially in Istria and Dalmatia, where it is known as the ferruginous red earth or *terra rossa.*[1]

Other remarkable examples of similar subaerial waste have been specially noticed among crystalline schists and eruptive rocks. In South America, it has been remarked with astonishment that the rocks are sometimes decayed to a depth of more than 300 feet.[2] In the southern portions of North America and in Central Asia the same fact has been observed. Pumpelly has specially drawn attention to the geological importance of this prolonged disintegration *in sitû*. He points out that as masses of decomposed rock may be observed to a depth of over 100 feet, the surface of the still solid rock underneath presents ridges and hollows, succeeding each other according to varying durability under the influence of percolating carbonated water. In this kind of weathering, where erosion does not come into play, it is evident that the resulting topography must, in some important respects, differ from that of an ordinary surface of superficial denudation. In particular, as Pumpelly shows, rock basins may be gradually eaten out of the solid rock. These will remain full of the decomposed material, but any subsequent action, such as that of glacier ice which could scoop out the detritus, would leave the basins and their intervening ridges exposed.[3]

[1] On the origin of "Terra rossa," see M. Neumayr, *Verhandl. Geol. Reichsanst.* 1875, p. 50. Th. Fuchs, *op. cit.* p. 194. E. von Mojsisovics, *Jahrb. Geol. Reichsanst.* xxx. (1880), p. 210. It is included among the ferruginous deposits by Stoppani ("Corso di Geologia," iii. p. 534).

[2] Liais, "Géologie du Brésil," p. 2. *Ann. des Mines*, 7me sér. viii. p. 698.

[3] Pumpelly, *Amer. Journ. Sci.* 3rd ser. xviii. 136; also *postea*, p. 416.

Formation of Soil.—On level surfaces of rock the weathered crust may remain with comparatively little rearrangement until plants take root on it, and by their decay supply organic matter to the decomposed layer, which eventually becomes what we term "vegetable soil." Animals also furnish a smaller proportion of organic ingredients. Though the character of soil depends primarily on the nature of the rock out of which it has been formed, its fertility arises in no small measure from the commingling of decayed animal and vegetable matter with decomposed rock.

A gradation may be traced from the soil downwards into what is termed the "subsoil," and thence into the solid rock underneath. Between soil and subsoil a marked difference in colour is often observable, the former being yellow or brown, when the latter is blue, grey, red, or other colour of the rock beneath. This contrast, evidently due to the oxidation and hydration especially of the iron, extends downwards as far as the subsoil is opened up by rootlets and fibres to the ready descent of rain-water. The yellowing of the subsoil may even occasionally be noticed around some stray rootlet which has struck down further than the rest, below the general lower limit of the soil (*postea*, Section iii.).

Mr. Darwin observed many years ago that a layer of soil three inches in depth had grown above a layer of burnt marl spread over the land fifteen years previously; also that in another example a similar layer had, as it were, sunk beneath the soil to a depth of twelve or thirteen inches in eighty years. He connected these facts with the work of the common earth-worm, and concluded that the fine loam which had grown above these original superficial layers had been carried up to the surface, and voided there in the familiar form of worm-castings.[1] This action of the earth-worm is doubtless highly important, but, as Richthofen has pointed out, we have to take also into account that gradual augmentation of level due to the daily deposit of dust (*ante* p. 321).

Soil being composed mainly of inorganic, and to a slight extent of

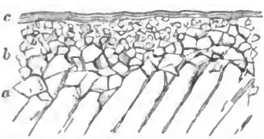

FIG. 92.—SECTION SHOWING THE UPWARD PASSAGE OF ROCK (*a*) INTO SUBSOIL (*b*) AND THENCE INTO VEGETABLE SOIL (*c*).

organic materials, the proportion between these two elements is a question of high economic importance. With regard to the organic matter, it is the experience of practical agriculturists in Britain that oats and rye will grow upon a soil with 1½ per cent. of organic

[1] *Geol. Trans.* v. 1840, p. 505.

matter, but that wheat requires from 4 to 8 per cent.[1] To a geologist this organic matter has much interest, as the source of most of the carbonic acid by which so wide a series of changes is worked by subterranean water. The inorganic portion of soil, or still undissolved residue of the original surface rock, varies from a loose open substance with 90 per cent. or more of sand, to a stiff cold retentive material with more than 90 per cent. of clay. When this sand and clay are more equally mixed they form a "loam."

Reference has just been made to the thick accumulation of rock decomposed *in sitû* observable in certain regions which, having been above the sea for a lengthened period, have been long exposed to the action of weathering. Where this action has been supplemented by that of rain, widespread formations of loam and earth have been gathered together. These are well illustrated by the "brick-earth," "head," and "rain-wash" of the south of England—earthy deposits, sometimes full of angular stones, derived from the subaerial waste of the rocks of the neighbourhood.[2]

2. **Mechanical Action.**—Besides chemically corroding rocks and thereby loosening the cohesion of their particles, rain acts mechanically by washing off these particles, which are held in suspension in the little rain-runnels or are pushed by them along the surface. The amount and rapidity of this action do not depend merely on the annual quantity of rain. A comparatively large rainfall may be so equably distributed through a year or season as to produce less change than may be caused by a few heavy rainstorms which, though inferior in total amount of precipitated moisture, descend rapidly in great volume. Such copious rains, by deluging the surface of a country and rapidly flooding its water courses, may transport in a few hours an enormous amount of sand and mud to lower levels. Another feature to be kept in view is the angle of declivity: the same amount of rain will perform vastly more mechanical work if it can swiftly descend a steep slope, than if it has to move tardily over a gentle one.

Removal and Renewal of Soil.—Élie de Beaumont drew attention to what appeared to be proofs of the permanence or long duration of the layer of vegetable soil.[3] But the cases cited by him are not inconsistent with the doctrine that the persistence of the soil is true rather of the layer as a whole than of its individual particles.[4] Were there no provision for its renewal, soil would

[1] Johnston's *Elements of Agricultural Chemistry*, p. 80.

[2] See Austen, *Q. J. Geol. Soc.* vi. p. 94, vii. p. 121; Foster and Topley, *op. cit.* xxi. p. 446. The vast extent of some superficial formations, like the "loess" above (p. 322) referred to, has often suggested submergence below the sea. But when, instead of marine organisms, only terrestrial, fluviatile, or lacustrine remains occur in them, as in the brick-clays and loess, the idea of marine submergence cannot be entertained. The remarkable "tundras" or steppes of Siberia, and the "black earth" of Russia, are examples of such extensive formations, which are certainly not of marine origin, but point to long-continued emergence above the sea. See Murchison, Keyserling, and De Verneuil's "Geology of Russia." Belt. *Q. J. Geol. Soc.* xxx. p. 490; also *postea*, p. 458.

[3] "Leçons de Géologie Pratique," i. p. 140.

[4] Geikie, *Trans. Geol. Soc. Glasgow*, iii. p. 170.

comparatively soon be exhausted and would cease to support the same vegetation. This result indeed occurs partially, especially on flat lands, but would be far more widespread were it not that rain, gradually washing off the upper part of the soil, exposes what lies beneath to further disintegration. This removal takes place even on grass-covered surfaces through the agency of earth-worms, by which fine particles of loam are brought up and exposed to the air to be dried and blown away by wind or washed down by rain. The lower limit of the layer of soil is thus made to travel downward into the subsoil, which in turn advances into the underlying rock. As Hutton long ago insisted, the superficial covering of soil is constantly, though slowly, travelling to the sea.[1] In this ceaseless transport rain acts as the great carrying agent. The particles of rock and of soil are step by step moved downward over the face of the land till they reach the nearest brook or river, whence their seaward progress may be rapid. A heavy rain discolours the water-courses of a country, because it loads them with the fine débris which it removes from the general surface of the land. In this way rain serves as the means whereby the work of the other disintegrating forces is made conducive to the general degradation of the land. The decomposed crust produced by weathering, which would otherwise accumulate over the solid rock and in some measure protect it from decay, is removed by rain, and a fresh surface is thereby laid bare to further decomposition.

Unequal Erosive Action of Rain.—While the result of rain action is the general lowering of the level of the land, this process necessarily advances very unequally in different places. On flat ground the waste may be quite inappreciable except after long intervals and by the most accurate measurements, or it may even give place to deposition, the fine detritus washed off the slopes being spread out so as actually to heighten the alluvial surface. In numerous localities great variations in the rate of erosion by rain may be observed. Thus, from the pitted, channelled ground lying immediately under the drip of the eaves of a house, fragments of stone and gravel stand up prominently, because the earth around and above them has been washed away by the falling drops, and because, being hard, they resist the erosive action and screen the earth below them. On a larger scale the same kind of operation may be noticed in districts of conglomerate, where the larger blocks, serving as a protection to the rock underneath, come to form as it were the capitals of slowly-deepening columns of rock (Fig. 93). In certain valleys of the Alps a stony clay is cut by the rain into pillars, each of which is protected by, and indeed owes its existence to, a large block of stone which lay originally in the heart of the mass (Fig. 94). These columns are of all heights, according to the positions in which the stones may have originally lain.

There are instances, however, where the disintegration has been

[1] *Theory of the Earth*, Part II. Chaps. V., VI.

so complete that only a few scattered fragments remain of a once extensive stratum, and where it may not be easy to realize that these fragments are not transported boulders. In Dorsetshire and Wiltshire, for example, the surface of the country is in some parts so thickly strewn with fragments of sandstone and conglomerate "that a person may almost leap from one stone to another without

Fig. 93.—Rain-eroded Pillars of Old Red Conglomerate, Fochabers.

touching the ground. The stones are frequently of considerable size, many being four or five yards across, and about four feet thick."[1] They are found lying abundantly on the Chalk, suggestive at first of some former agent of transport by which they were brought from a distance. They are now, however, generally admitted to be simply fragments of some of the sandy Tertiary strata which once covered the districts where they occur. While the softer portions of these strata have been carried away, the harder parts (their hardness perhaps increasing by exposure) have remained behind as "Grey Wethers," and have subsequently suffered from the inevitable splitting and crumbling action of the weather. Similar blocks of quartzite and conglomerate referable to the disintegration of Lower Tertiary beds *in sitû*, are traceable in the north-east of

[1] They have been used for the huge blocks of which Stonehenge and other of the so-called druidical circles have been constructed, hence they have been termed Druid Stones. Other names are Sarsen Stones (supposed to indicate that their accumulation has been popularly ascribed to the Saracens), and Grey Wethers, from their resemblance in the distance to flocks of (wether) sheep. See *Descriptive Catalogue of Rock Specimens in Jermyn Street Museum*, 3rd ed.; Prestwich, *Q. J. Geol. Soc.* x. p. 123; Whitaker, *Geological Survey Memoir on parts of Middlesex*, &c. p. 71.

France up into the Ardennes, showing that the Tertiary deposits of the Paris basin once had a far wider extension than they now possess.[1] On a far grander scale the apparent caprice of general subaerial disintegration is exhibited among the "buttes" and "bad-lands" of Wyoming and the neighbouring territories of North America. Colossal pyramids, barred horizontally by the level lines of stratifica-

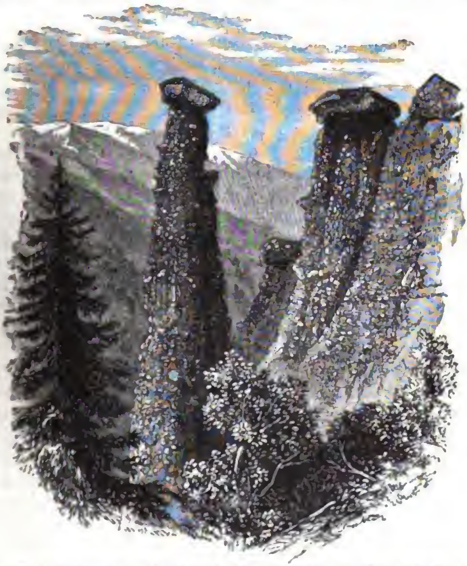

FIG. 94.—EARTH-PILLARS LEFT BY THE WEATHERING OF MORAINE-STUFF, TYROL.

tion, rise up one after another far out into the plains, which were once covered by a continuous sheet of the formations whereof these detached outliers are only fragments.

As a consequence of this inequality in the rate of waste depending on so many conditions, notably upon declivity, amount and heaviness of rain, lithological texture and composition, and geological structure, great varieties of contour are worked out upon the land. A survey of this department of geological activity shows, indeed, that the unequal wasting by rain has in a large measure produced the details of relief on the present surface of the continents, those tracts where the destruction has been greatest forming hollows and valleys, others, where it has been less, rising into ridges and hills. Even the minuter features of crag and pinnacle may be referred to a similar origin. (Book VII.)

[1] Barrois, *Ann. Soc. Géol. du Nord*, vi. p. 366.

§ 2. Underground Water.

A great part of the rain that falls on land sinks into the ground and apparently disappears; the rest flowing off into runnels, brooks, and rivers, moves downward to the sea. It is most convenient to follow first the course of the subterranean water.

All rocks being more or less porous, and traversed by abundant joints and cracks, it results that from the bed of the ocean, from the bottoms of lakes and rivers, as well as from the general surface of the land, water is continually filtering downward into the rocks beneath. To what depth this descent of surface water may go is not known. As stated in a former section, it may reach as far as the intensely heated interior of the planet, for, as the already quoted researches of Daubrée have shown, capillary water can penetrate rocks even against a high counter-pressure of vapour (*ante*, p. 299). Probably the depth to which the water descends varies indefinitely according to the varying nature of the rocky crust. Some shallow mines are practically quite dry, others of great depth require large pumping engines to keep them from being flooded by the water that pours into them from the surrounding rocks. Yet as a rule, the upper layers of rock in the earth's crust are fuller of moisture than those deeper down.

Underground Circulation and Ascent of Springs.—The water which sinks below ground is not permanently removed from the surface, though there must be a slight loss due to absorption and chemical alteration of rocks. Finding its way through joints, fissures, or other divisional planes of rocks, it issues once more at the surface in springs. This may happen either by continuous descent to the point of outflow or by hydrostatic pressure. In the former case, rain-water sinking underneath, flows along a subterranean channel until, when that channel is cut by a valley or other depression of the ground, the water emerges again to daylight. Thus

Fig. 95.—Simple or Surface Springs.

in a district having a simple geological structure (as in Fig. 95), a sandy porous stratum (*e*), through which water readily finds its way, may rest on a less easily permeable clay (*d*), followed underneath by a second sandy pervious bed (*c*), resting as before upon comparatively impervious[1] strata (*a*). Rain falling upon the upper sandy stratum (*e*), will sink through it to the surface of the clay (*d*),

[1] This term *impervious* must evidently be used in a relative and not in an absolute sense. A stiff clay is practically impervious to the trickle of underground water; hence its employment as a material for puddling (that is, making water-tight) canals and reservoirs. But it contains abundant interstitial water, on which indeed its characteristic plasticity depends.

along which it will flow until it issues either as springs or in a general line of wetness along the side of the valley (*b*). The second sandy bed (*c*) will serve as a reservoir of subterranean water so long as it remains below the surface, but any valley cutting down below its base towards or beyond *b* will drain it.

Except, however, in districts of gently inclined and unbroken strata, springs are more usually of the second class, where the water has descended to a greater or less distance from the surface and has risen again to the surface in fissures, as in so many syphons. Lines of joint and fault afford ready channels for subterranean drainage (Fig. 96). Powerful faults which bring different kinds of rock against

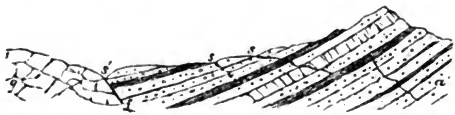

FIG. 96.—DEEP-SEATED SPRINGS RISING THROUGH JOINTS (*s s*) AND A FAULT (*f*).

each other are frequently marked at the surface by copious springs (*f*. Fig. 96). So complex is the network of divisional planes by which rocks are traversed that water may often follow a most labyrinthine course before it completes its underground circulation (Fig. 97). In most districts rocks are permeated with water below a certain limit termed the *water-level*. Owing to varying structure and relative capacity for water among rocks, this line is not strictly horizontal like that of the surface of a lake. Moreover, it is liable to rise and fall according as the seasons are wet or dry. In some places it lies quite near, in others far below, the surface. A well is an artificial hole dug down below the water-level, so that the water

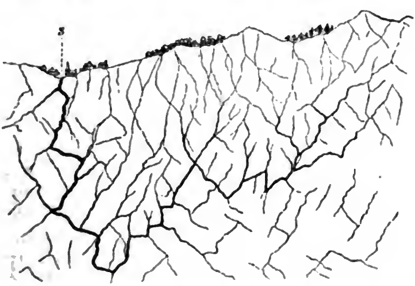

FIG. 97.—INTRICATE SUBTERRANEAN COURSE OF PERCOLATING WATER.

may percolate into it. Hence, when the water-level happens to be at a small depth wells are shallow, when at a great depth they require to be deep.

Since rocks vary greatly in porosity, some contain far more water than others. It often happens that, percolating along some porous bed, subterranean water finds its way downward until it passes under some more impervious rock. Hindered in its progress, it accumulates in the porous bed, from which it may be able to find its way up to the surface again only by a tedious circuitous passage. If, however, a bore-hole be sunk through the upper impervious bed down to the water-charged stratum below, the water will avail itself of this

Fig. 98.—Diagram illustrative of the Theory of Artesian Wells.
a, *b*, Lower water-bearing rocks, covered by an impervious series (*c*), through which, at *l* and elsewhere borings are made to the water level beneath.

artificial channel of escape, and will rise in the hole, or even gush out as a *jet d'eau* above ground. Wells of this kind are now largely employed. They bear the name of *Artesian*, from the old province of Artois in France, where they have long been in use.[1]

That the water really circulates underground, and passes not merely through the pores of the rocks but in crevices and tunnels, which it has no doubt to a large extent opened for itself along natural joints and fissures, is proved by the occasional rise of leaves, twigs, and even live fish, in the shaft of an Artesian well. Such testimony is particularly striking when found in districts without surface waters, and even perhaps with little or no rain. It has been met with, for instance, in sinking wells in some of the sandy deserts on the southern borders of Algeria.[2] In these and similar cases it is clear that the water may, and sometimes does, travel for many leagues underground away from the district where it fell as rain or snow, or where it leaked from the bed of a river or lake.

The temperature of springs affords a convenient, but not always quite reliable indication of the relative depth from which they have risen. Some springs are just one degree or less above the temperature of ice (C. 0°, Fahr. 32°). Others in volcanic districts issue with the temperature of boiling water (C. 100°, Fahr. 212°). Between these two extremes every degree may be registered. Very cold springs may be regarded as probably deriving their supply from cold or snow-covered mountains. Certain exceptional cases, however, occur where ice forms in caverns (*glacières*) even in warm and comparatively low districts. Water issuing from these ice-caves is of course cold.[3] On the other hand, springs whose temperature is higher than the mean temperature of the places at which they emerge must have been warmed by the internal

[1] See Prestwich, *Q. J. Geol. Soc.* xxviii. p. lvii. and the references there given.

[2] Desor, *Bull. Soc. Sci. Nat. Neufchâtel*, 1864.

[3] The most remarkable example of a glacière yet observed is that of Dobschau, in Hungary, of which an account, with a series of interesting drawings, was published in 1874 by Dr. J. A. Krenner, keeper of the national museum in Buda-Pesth.

heat of the earth. These are termed *Thermal Springs.*[1] The hottest springs are found in volcanic districts. But even at a great distance from any active volcano, springs rise with a temperature of 120° Fahr. (which is that of the Bath springs) or even more. These have probably ascended from a great depth. If we could assume a progressive increase of 1° Fahr. of subterranean heat for every 60 feet of descent, the water at 120°, issuing at a locality whose ordinary temperature is 50°, should have been down at least 4200 feet below the surface. But from what has been already stated (p. 47) regarding the irregular stratification of temperature within the earth's crust, such estimates of the probable depth of the sources of springs are not quite reliable. The source of heat in these cases may be some crushing of the crust or ascent of heated matter from underneath, which does not however produce volcanic phenomena.

I. Chemical Action.—Every spring, even the clearest and most sparkling, contains dissolved gases, also solid matter abstracted from the soils and rocks which it has traversed. The gases include those absorbed by rain from the atmosphere (p. 330), also carbon dioxide supplied by decomposing organic matter in the soil, sulphuretted hydrogen, and marsh gas or other hydrocarbon derived from decompositions within the crust.

The solid constituents consist partly of organic, but chiefly of mineral matter. Where spring water has been derived from an area covered with ordinary humus, organic matter is always present in it. Organic acids are abstracted from the soil by descending water, and these, before they are oxidized into carbonic acid, appear to be effective in decomposing minerals and forming soluble salts (p. 433). The mineral matter of spring water consists principally of carbonates of calcium, magnesium, and sodium, sulphates of calcium and sodium, and chloride of sodium, with minute traces of silica, phosphates, nitrates, &c. The nature and amount of mineral impregnation depend on the one hand upon the chemical energy of the water, and on the other upon the composition of the rocks. Various sources of augmentation of its chemical energy are available for subterranean water. (1.) The abundant organic matter in the soil partially abstracts oxygen from the water, but supplies organic acids, especially carbonic acid. In so far as the water carries down from the soil any oxidizable organic substance its action must be to reduce oxides. Ordinary vegetable soil possesses the power of removing from permeating water potash, silica, phosphoric acid, ammonia, and organic matter, elements which had been already in great measure abstracted from it by living vegetation, and which are again ready to be taken up by the same organic agents. (2.) Carbon dioxide is here

[1] Studer points out that some springs which are thermal in high latitudes or at great elevations, would be termed cold springs near the equator, and, consequently, that springs having a lower temperature than that of the inter-tropical zone, that is from C. 0° to 30° (Fahr. 32°–84°), should be called "relative," those which surpass that limit (C. 30°–100°) "absolute," and he gives a series illustrative of each group—"Physikalische Geographie," ii. (1847), p. 49. For volcanic thermal springs see *ante*, p. 236.

and there largely evolved within the earth's crust, especially in regions of extinct or dormant volcanoes. Subterranean water coming in the way of this gas dissolves it, and thereby obtains augmented solvent power. (3.) The capacity of water for dissolving mineral substances is augmented by increase of temperature (*ante*, p. 300). It is conceivable that cold springs containing a large percentage of mineral solutions may have acquired this impregnation at a great depth and at a higher temperature. As a rule, however, thermal water as it cools will deposit its dissolved minerals on the walls of the fissures up which it ascends. Hence no doubt the successive layers in mineral veins. (4.) Pressure likewise raises the solvent power of water (p. 300). (5.) Some of the solutions due to decompositions effected by the water, increase its ability to accomplish further decompositions (p. 302). Thus the alkaline carbonates, which are among the earliest products, enable it to dissolve silica and decompose silicates. These carbonates likewise promote the decomposition of some sulphates and chlorides. Calcium carbonate, which is found in the water of most springs, is the result of decomposition, and by its presence leads to the further disintegration of various minerals. "Carbonic acid, bicarbonate of lime, and the alkaline carbonates bring about most of the decompositions and changes in the mineral kingdom. It is a matter of great importance to find that the same substances which give rise to so many decompositions in the mineral kingdom are the chief ingredients in the waters."[1]

The nature of the changes effected by the percolation of water through subterranean rocks will be best understood from an examination of the composition of spring water. Springs may be conveniently though not very scientifically grouped into two classes. 1st: Common springs, such as are fit for ordinary domestic purposes, and 2nd, mineral springs, in which the proportions of dissolved mineral matter are so much higher as to remove the water from the usual potable kinds.

Common Springs possess a temperature not higher but frequently lower than that of the localities at which they rise, and ordinarily contain, besides atmospheric air and its gases, calcic carbonate and sulphate, common salt, with chlorides of calcium and magnesium, and sometimes organic matter. The amount of dissolved mineral contents in ordinary drinking water does not exceed ·5, or at most 1·0 gramme per litre; the best waters contain even less. The amount of organic matter should not exceed from ·005 to ·01 gramme per litre in wholesome drinking water.[2] Spring water containing a very minute percentage of mineral matter, or in which this matter, even if in more considerable quantity, consists chiefly of alkaline salts, dissolves common soap readily, and is known in domestic economy as "soft" water. Where, on the other hand, the salts in solution are calcic or magnesic carbonates, sulphates, or chlorides,

[1] Bischof, *Chem. Geol.* i. p. 17.
[2] Dr. B. H. Paul in *Watts' Dict. Chem.* v. p. 1022.

they decompose soap, forming with its fatty acids insoluble compounds which appear in the familiar white curdy precipitate. Such water is termed "hard." Where the hardness is due to the presence of bicarbonates it disappears on boiling, owing to the loss of carbonic acid and the consequent precipitation of the insoluble carbonate, while in the case of sulphates and chlorides no such change takes place.[1]

The extensive investigations carried on by the Rivers Pollution Commission in Britain have thrown much light on the relation between the amount of mineral matter in solution in springs and wells, and the character of the underlying rock. The following table gives a summary of results obtained:

	No. of Analyses.	Mean amount of Solid Contents in 10,000 Parts of Water.
1. Fluviomarine Drift Gravel	10	6·132
2. Upper Chalk	30	2·984
3. Lower Chalk to Upper Greensand	19	3·005
4. Oolites	35	3·033
5. Lias	7	3·641
6. New Red Sandstone	15	2·869
7. Magnesian Limestone	1	4·418
8. Coal Measures	14	2·430
9. Yoredale and Millstone Grit	8	1·773
10. Mountain Limestone	13	3·206
11. Devonian and Old Red Sandstone	32	2·506
12. Silurian	15	1·233
13. Granite and Gneiss	8	0·594

From this table it is evident how greatly the proportion of dissolved mineral substance augments in those waters which rise in calcareous tracts, and how it correspondingly sinks in those where the rocks are mainly siliceous. The maximum percentage in group No. 13 was less than 1 part in every 10,000 of water, the minimum being 0·140 from granite. In No. 1, on the contrary, the maximum was 22·524, in No. 6 it was 7·426, and in No. 10 it was 9·850.[2]

Mineral springs are in some instances cold, in others warm, or even boiling. Thermal springs are more usually mineral waters than cold springs, but there does not appear to be any necessary relation between temperature and chemical composition. Mineral springs may be roughly classified for geological purposes according to the prevailing mineral substance contained in them, which may range in amount from 1 to 300 grammes per litre.[3]

Calcareous Springs contain calcium carbonate in such quantity as to be readily deposited in the form of a white crust round objects over which the water flows. Calcium carbonate, according to Fresenius, is dissolved by 10,600 of cold and by 8834 parts of warm water.[4] But in nature the proportion of this carbonate present in springs depends mainly on the proportion of carbonic acid which retains the lime in solution. On the loss of carbonic acid by

[1] Paul, *loc. cit.*
[2] "Rivers Pollution Commission Report," 1874, p. 187.
[3] Paul, *op. cit.* p. 1016.
[4] Roth, "Chem. Geol." i. p. 48. "One litre of water, either cold or boiling, dissolves about 18 milligrammes." Roscoe and Schorlemmer, "Chemistry," ii. p. 208.

exposure and evaporation, the carbonate is thrown down as a white precipitate. Water saturated with carbonic acid will at the freezing point dissolve 0·70 gramme and at 10° C., 0·88 gramme of calcium carbonate per litre. Calcareous springs occur abundantly in limestone districts, and indeed may be looked for wherever the rocks are of a markedly calcareous character. In some regions they have brought up such enormous quantities of lime as to form considerable hills (*postea*, p 354).

Ferruginous or Chalybeate Springs contain a large proportion of iron in the total mineral ingredients, and are known by their inky taste, and the yellow, brown, or red ochry deposit along their channel. They may be frequently observed in districts where beds or veins of ironstone occur, or where the rocks contain much iron in combination, particularly in the waters of old mines. In many cases the iron is supplied by the weathering of the sulphide (marcasite) so abundantly contained among stratified rocks. Ferrous sulphate is produced and brought to the surface, but in presence of carbonates, particularly of the ubiquitous carbonate of lime, this sulphate is decomposed, the acid being taken up by the alkaline earth or alkali and the iron becoming a ferrous carbonate, which rapidly oxidizes and falls as the familiar yellow or brown crust of hydrous peroxide. The rapidity with which ferrous-carbonate is thus oxidized and precipitated was well shown by Fresenius in the case of the Langenschwalbach chalybeate spring. In its fresh state the water contains in 1000 parts 0·37696 of protoxide of iron. After standing twenty-four hours it was found to contain only 87·7 per cent. of the original amount of iron; after sixty hours 62·9 per cent., and after eighty-four hours 53·2 per cent.[1]

Brine Springs (Soolquellen) bring to the surface a solution in which sodium chloride greatly predominates. Springs of this kind appear where beds of solid rock-salt exist underneath, or where the rocks are impregnated with the mineral. Most of the brines worked as sources of salt are derived from artificial borings into saliferous rocks. Those of Cheshire in England, the Salzkammergut in Austria, Bex in Switzerland, &c., have long been well known. Some of the English brines contain about one per cent. of salts, of which chloride of sodium may range from a half to three-fourths or more. Other brines, however, yield a far larger amount; one at Clemenshall, Würtemberg, gave upwards of 26 per cent. of salts, of which almost the whole was chloride of sodium. The other substances contained in solution in the water of brine springs are chlorides of potassium, magnesium, and calcium; sulphates of calcium and less frequently of sodium, potassium, magnesium, barium, strontium, or aluminium; silica; compounds of iodine and fluorine; with phosphates, arseniates, borates, nitrates, organic matter, carbon dioxide, sulphuretted hydrogen, marsh gas, and nitrogen.[2]

[1] *Journal für Prakt. Chem.* lxiv. 368, quoted by Roth, *op. cit.* i. p. 565.
[2] Roth, *Chem. Geol.* i. p. 442. Bischof, *Chem. Geol.* ii.

Medicinal Springs, a vague term applied to mineral springs which have or are believed to have curative effects in different diseases. Medical men recognize various qualities, distinguished by the particular substance most conspicuous in each variety of water—as *Alkaline Waters,* containing lime or soda and carbonic acid, as those of Vichy or Saratoga; *Bitter Waters,* with sulphate of magnesia and soda—Sedlitz, Kissingen; *Salt* or *Muriated Waters,* with common salt as the leading mineral constituent—Wiesbaden, Cheltenham; *Earthy Waters,* lime, either a sulphate or carbonate, being the most marked ingredient—Bath, Lucca; *Sulphurous Waters,* with sulphur as sulphuretted hydrogen and in sulphides—Aix-la-Chapelle, Harrogate. Some of these medicinal springs are thermal waters. Even where no longer warm, the water may have acquired its peculiar medicinal characters at a great depth, and therefore under the influence of increased temperature and pressure. Sulphur springs are sometimes warm, but also occur abundantly cold, where the water rises through rocks containing decomposing sulphides and organic matter. Sulphates are there first formed, which by the reducing effect of the organic matter are decomposed, with the resultant formation of sulphuretted hydrogen (p. 64). In some cases sulphuretted hydrogen or sulphurous acid is oxidized into sulphuric acid, which remains free in the water.[1]

Oil Springs.—Petroleum is sometimes brought up in drops floating in spring-water (St. Catherine's near Edinburgh). In many countries it comes up by itself or mingled with inflammable gases. Reference has already (p. 173) been made to the abundance of this product in North America. In western Pennsylvania some oil-wells have yielded as much as 2000 to 3000 barrels of oil per day. That the oil, which is specially confined to particular layers of rock, arises from the alteration of organic substances embedded in the rocks of the crust, can hardly be doubted, but no satisfactory explanation has been given of the probable nature and distribution of the organisms which yielded the oil.

Results of the Chemical Action of Underground Water.—Three remarkable results of the chemical operations of underground water are, 1st: The internal composition and minute structure of rocks are altered. 2nd: Enormous quantities of mineral matter are carried up to the surface, where they are partly deposited in visible form, and partly conveyed by brooks and rivers to the sea. 3rd: As a consequence of this transport, subterranean tunnels, passages, caverns, grottoes, and other cavities of many varied shapes and dimensions are formed.

1. *Alteration of Rocks.*—The four processes of oxidation, deoxidation, solution, and hydration, described (p. 331) as carried on above ground by rain, are likewise in progress on a great scale underneath. Since the permeability of subterranean rocks permits water to find its way through their pores as well as along their divisional planes,

[1] Roth, *op. cit.* i. pp. 444, 452.

chemical changes, of a kind like those in ordinary weathering, take place in them, and at some depth may be intensified by internal terrestrial heat. This subterranean alteration of rocks may consist in the mere addition of substances introduced in chemical solution; or in the simple solution and removal of some one or more constituents; or in a complex process of removal and replacement wherein the original substance of a rock is molecule by molecule removed, while new ingredients are simultaneously or afterwards substituted. In tracing these alterations of rocks the study of pseudomorphs becomes important, for we thereby learn what was the original composition of the mineral or rock. The mere existence of a pseudomorph points to the removal and substitution of mineral matter by permeating water.[1]

The extent to which such mineral replacement has been carried among rocks of the most varied structure and composition is probably best shown by the abundant petrified organic forms in formations of all geological ages. The minutest structures of plants and animals have been, particle by particle, removed and replaced by mineral matter introduced in solution, and this so imperceptibly and yet thoroughly, that even minutiæ of organization, requiring a high power of the microscope for their investigation, have been preserved without distortion or disarrangement. From this perfect condition of preservation gradations may be traced until the organic structure is gradually lost amid the crystalline or amorphous infiltrated substance (Fig. 99). The most important petrifying media in nature are calcium carbonate, silica, and disulphide of iron (marcasite more usually than pyrite) (see Book V.).

Fig. 99.—Fossil wood from tuff, Burntisland, showing parts perfectly preserved and parts destroyed by Crystallization of Calcite. Magnified 10 Diameters.

Another proof of the alteration which superficial rocks have suffered from permeating water is supplied by the abundance of veins of calcite and quartz by which they are traversed, these minerals having been introduced in solution and often from the decomposition of the enclosing rock. As Bischof pointed out, a drop of acid seldom fails to give effervescence on pieces of crystalline rock which have been taken even at some little depth from the surface, thus indicating the decomposition and deposit caused by permeating water. As already stated, one of the most remarkable

[1] It is not needful to take account here of such exceptional cases as the artificial conversion of aragonite into calcite by exposure to a high temperature. In such paramorphs the change is a molecular or crystalli:.: rather than a chemical one, though how it takes place is still unknown.

results of the application of the microscope to geological inquiry is the extent to which it has revealed these all-pervading alterations even in what might be supposed to be perfectly fresh rocks. Among the silicates the most varied and complex interchanges have been effected. Besides the production of calcium carbonate by the decomposition of such minerals as the lime-felspars, the series of hydrous green ferruginous silicates (delessite, saponite, chlorite, serpentine, &c.), so commonly met with in crystalline rocks, are usually witnesses of the influence of infiltrating water. The changes visible in the olivine of basalt (p. 77) offer instructive lessons of the progress of transformation. One further example may be cited as supplied by the zeolites, so common in cavities and veins among many ancient volcanic and other crystalline rocks. These appear to have commonly resulted from the decomposition of felspars or allied minerals. Their mode of formation is indicated by the observation already cited (p. 300), that Roman masonry at the baths of Plombières has in the course of centuries been so decomposed by the slow percolation of alkaline water at a temperature not exceeding 50° C. (122° Fahr.) under ordinary atmospheric pressure that various zeolitic silicates have been developed in the brick.[1]

2. *Chemical Deposits.*—Of these by far the most abundant is calcium carbonate. The way in which this substance is removed and re-deposited by permeating water can be instructively studied in the formation of the familiar *stalactites* and *stalagmites* beneath damp arches and in limestone caves. As each drop gathers on the roof and begins to evaporate and lose carbonic acid, the excess of carbonate which it can no longer retain is deposited round its edges as a ring. Drop succeeding drop lengthens the original ring into a long pendent tube, which, by subsequent deposit inside, becomes a solid stalk, and on reaching the floor may thicken into a massive pillar. At first the calcareous substance is soft, and when dry pulverulent, but it becomes by degrees crystalline. Each stalactite is found to possess an internal radiating fibrous structure, the fibres passing across the concentric zones of growth. The stalactite remains saturated with calcareous water, and the divergent prisms are developed and continued as radii from the centre of the stalk.

FIG. 100.—SECTION OF PART OF A STALACTITE. MAGNIFIED 10 DIAMETERS.

This process may be completed within a short period. At the North Bridge, Edinburgh, for example, which was erected in 1772, stalactites were obtained in 1874, some of which measure an inch and a half in diameter and possess the characteristic radiating structure.

[1] Daubrée, "Géologie Expérimentale," 179, *et seq.*

It is doubtless by an analogous process that limestones, originally composed of the débris of calcareous organisms and interstratified among perfectly unaltered shales and sandstones, have acquired a crystalline structure.[1]

Calcareous springs deposit abundantly a precipitate of carbonate of lime upon mosses, twigs, leaves, stones and other objects. The precipitate takes place when from any cause the water parts with carbonic acid. This may arise from mere evaporation, but is probably mainly caused by the action of bog mosses and water plants, which, decomposing the carbonic acid, cause a crust of carbonate of lime to be deposited round their stems and branches (*postea*, p. 461). Hence calcareous springs are popularly called "petrifying," though they merely encrust organic bodies and do not convert them into stone. Calc-sinter, as this precipitate is called, may be found in course of formation in most limestone districts, sometimes in masses large enough to form hills and compact enough to furnish excellent building stone. The travertine of Tuscany is deposited at the Baths of San Vignone at the rate of six inches a year, at San Filippo one foot in four months. At the latter locality it has been piled up to a depth of at least 250 feet, forming a hill a mile and a quarter long and the third of a mile broad.[2]

Chalybeate springs give rise to a deposit of hydrous peroxide of iron. This has already been referred to as a yellow and brown deposit along the channels of the water. But in undrained districts of temperate latitudes in Northern Europe and America much iron is also deposited beneath soil which rests on a retentive subsoil. When the descending water is arrested on this subsoil the iron, in solution as organic salts that oxidize into ferrous carbonate, is gradually converted into the insoluble hydrous ferric oxide which is precipitated and forms a dark ferruginous layer known to Scottish farmers as "moorband pan." So effectually does this layer interrupt the drainage that the soil remains permanently damp and unfertile. But when the "pan" is broken up and spread over the surface it quickly disintegrates, and improves the soil, which can then be properly drained (*postea*, p. 463).

Siliceous springs form important masses of various sinters round the point of outflow. The basins and funnels of geysers have already been described (p. 236). One of the sinter-beds in the Iceland geyser region is said to be two leagues long, a quarter of a league wide, and a hundred feet thick. Enormous beds of similar material have been formed in the Yellowstone geyser region. Such accumulations point to proximity to volcanic centres, or at least to the escape of hot water to the surface.

[1] Sorby, Address to Geological Society, *Q. J. Geol. Soc.* 1879, p. 42, *et seq.* The finely fibrous structure seen in calcedony under the microscope with polarized light passes in a similar way through the bands of growth of pebbles.

[2] Lyell, "Principles," i. p. 402. The student will find much detail regarding the abstraction and deposit of carbonate of lime by subterranean water in a paper by Senft, "Die Wanderungen und Wandelungen des kohlensauren Kalkes," *Z. Deutsch. Geol. Ges.* xiii. p. 263.

3. *Formation of subterranean channels and caverns.*—Measurement of the yearly amount of mineral matter brought up to the surface by a spring furnishes an approximate idea of the extent to which underground rocks undergo continual loss of substance. The warm springs of Bath, for example, with a mean temperature of 120° Fahr., are impregnated with sulphates of lime and soda, and chlorides of sodium and magnesium. Professor Ramsay has estimated their annual discharge of mineral matter to be equal to a square column 9 feet in diameter and 140 feet in height. Again, the St. Lawrence spring at Louèche (Leuk) discharges every year 1620 cubic metres (2127 cubic yards) of dissolved sulphate of lime, equivalent to the lowering of a bed of gypsum one square kilometre (0·3861 square mile) in extent, more than 16 décimètres (upwards of five feet) in a century.[1]

By prolonged abstraction of this nature subterranean tunnels, channels, and caverns have been formed. In regions abounding in rock-salt deposits, the result of the solution and removal of these by underground water is visible in local sinkings of the ground and the consequent formation of pools and lakes. The landslips and meres of Cheshire are illustrations of this process. In calcareous districts, however, more striking effects are observable. The ground may there be found drilled with vertical cavities (*swallow-holes, sinks, dolinas*) by the solution of the rock along lines of joint that serve as channels for

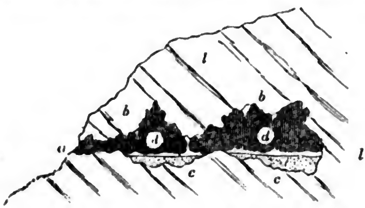

FIG. 101.—SECTION OF A LIMESTONE CAVERN (*B.*).

l l, A limestone hill, perforated by a cavern (*b b*) which communicates with the valley (*v*) by an opening (*a*). The bottom of the cavern is covered with ossiferous loam, above which lies a layer of stalagmite (*d d*), while stalactites hang from the roof, and by joining the floor separate the cavern into two chambers.

descending rain-water. Surface drainage, thus intercepted, passes at once underground, where, in course of time, an elaborate system of spacious tunnels and chambers may be dissolved out of the solid rock. Such has been the origin of the Peak caverns of Derbyshire, the intricate grottoes of Antiparos and Adelsberg, and the vast labyrinths of the Mammoth Cave of Kentucky. In the course of time the underground rivers open out new courses, and leave their old ones dry, as the Poik has done at Adelsberg. By the falling in of the roofs of caverns a communication is established with the surface,

[1] E. Reclus. "La Terre," i. p. 340.

and land-shells and land-animals fall into the holes, or the caverns are used as dens by beasts of prey, so that the remains of terrestrial animals are preserved under the stalagmite. Not unfrequently, caverns, once open and freely used as haunts of carnivora, have had their entrances closed by the fall of débris, as at *d* in Fig. 102,

Fig. 102.—Section of a Limestone Cavern with fallen-in Roof and concealed Entrance (*B*.).

where also the partial filling up of a cavern (*a a*) from the same cause is seen. Where the collapse of a cavern roof takes place below a watercourse the stream is engulfed. In this way brooks

Fig. 103.—Section of the Channel of an Underground Stream.

and rivers suddenly disappear from the surface, and after a long subterranean course, issue again in a totally different surface area of river-drainage from that in which they took their rise, and sometimes

with volume enough to be navigable almost up to their outflow. In such circumstances lakes, either temporary, like the Lake Zirknitz in Carniola, or perennial, may be formed over the sites of the broken-in caverns; and valleys may thus be deepened, or perhaps even formed. Mud, sand, and gravel, with the remains of plants and animals, are swept below ground, and sometimes accumulate in deposits of loam and breccia so often found in ossiferous caverns (Figs. 101 and 102).

II. Mechanical Action.—In its passage along fissures and channels, underground water not merely dissolves and removes materials in solution, it likewise loosens finer particles and carries them along in mechanical suspension. This removal of material sometimes produces remarkable surface changes along the side of steep slopes or cliffs. A thin porous layer, such as loose sand or ill-compacted sandstone, lying between more impervious rocks, such as masses of clay or limestone, and sloping down from higher ground, so as to come out to the surface near the base of a line of abrupt cliff, serves as a channel for underground water which issues in springs or in a more general oozing at the foot of the declivity. Under these circumstances the support of the overlying mass of rock is apt to be loosened; for the water not only removes piecemeal the sandy layer on which that overlying mass rests, but as it were lubricates the rock underneath. Consequently at intervals portions of the upper rock break off and slide down into the valley or plain below. Such dislocations are known as *landslips*.

Along sea-coasts and river valleys, at the base of cliffs subject to continual or frequent removal of material by running water, the phenomena of landslips are best seen. The coast line of the British Islands abounds with instructive examples. On the shores of Dorsetshire, for instance (Fig. 104), impervious Liassic clays (*a*) are over-

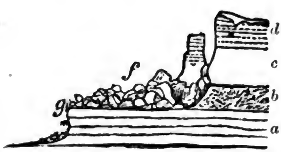

FIG. 104.—SECTION OF LANDSLIP FORMING UNDERCLIFF, PINHAY, LYME-REGIS (*B.*).

laid by porous greensand (*b*), above which lies chalk (*c*) capped with gravel (*d*). In consequence of the percolation of water through the sandy zone (*b*) the support of the overlying mass is destroyed, and hence from time to time segments are launched down towards the sea. In this way a confused medley of mounds and hollows (*f*) forms a characteristic strip of ground termed the "Undercliff" on this and other parts of the English coasts. This recession of the upper or inland cliff through the operation of springs is here more

rapid than that of the lower cliff (*g*) washed by the sea.[1] In the year 1839, after a season of wet weather, a mass of chalk on the same coast slipped over a bed of clay into the sea, leaving a rent three-quarters of a mile long, 150 feet deep, and 210 feet wide. The shifted mass, bearing with it houses, roads, and fields, was cracked, broken, and tilted in various directions, and was thus prepared for further attack and removal by the waves.[2] Of the antiquity of many landslips interesting proof is supplied by the ancient buildings occasionally to be seen upon the fallen masses. There would seem in these cases to have been comparatively little alteration of the scenery for many centuries. The undercliff of the Isle of Wight, the cliffs west of Brandon Head, county Kerry, the basalt escarpments of Antrim, and the edges of the great volcanic plateau of Mull, Skye, and Raasay, furnish illustrations of such old and prehistoric landslips.

On a more imposing scale, and interesting from its melancholy circumstances being so well known, was the celebrated fall of the Rossberg, a mountain (*a*, Fig. 105) situated behind the Righi in Switzerland, rising to a height of more than 5000 feet above the sea. After the rainy summer of 1806, a large part of one side of the mountain, consisting of steeply sloping beds of hard red sandstone and conglomerate (*b*), resting upon soft sandy layers (*c c*), gave way. The lubrication of the lower surface by the water having loosened the cohesion of the overlying mass, thousands of tons of solid rock, set loose by mere gravitation, suddenly swept across the valley of Goldau (*d*), burying about a square German mile of fertile land, four villages containing 330 cottages and outhouses, with 457 inhabitants.[3] In 1855 a mass of débris, 3500 feet long, 1000 feet wide, and 600 feet high, slid into the valley of the Tiber, which, dammed back by the obstruction, overflowed the village of San Stefano to a depth of 50 feet, until drained off by a tunnel.

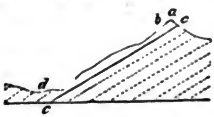

Fig. 105.—Section illustrating the Fall of the Rossberg.

§ 3. Brooks and Rivers.

These will be considered under four aspects:—(1) their sources of supply, (2) their discharge, (3) their flow, and (4) their geological action.

I. Sources of Supply.—Rivers, as the natural drains of a land surface, carry out to sea the surplus water after evaporation, together with a vast amount of material worn off the land. Their liquid

[1] De la Beeche "Geol. Observer," p. 22.

[2] Conybeare and Buckland's *Axmouth Landslip*, London, 1840. Lyell, "Principles," i. p. 536.

[3] Zay, "Goldau und seine Gegend." A small landslip took place at the same locality in August, 1874. Baltzer, *Neues Jahrb.* 1875, p. 15. Upwards of 150 destructive landslips have been chronicled in Switzerland. Riedl, *Neues Jahrb.* 1877, p. 916.

contents are derived partly from rain (including mist and dew) and melted snow, partly from springs. In a vast river system like that of the Mississippi, where the area of drainage is so extensive as to embrace different climates and varieties of rainfall, the amount of discharge, being in a great measure independent of local influences of weather, remains tolerably uniform or is subject to regular periodically recurrent variations. In smaller rivers, such as those of Britain, whose basins lie in a region having the same general features of climate, the quantity of water is regulated by the local rainfall. A wet season swells the streams, a dry one diminishes them. Hence, in estimating and comparing the geological work done by different rivers, we must take into account whether or not the sources of supply are liable to occasional great augmentation or diminution. In some rivers there is a more or less regularly recurring season of flood followed by one of drought. The Nile, fed by the spring rains of Abyssinia, floods the plains of Egypt every summer, rising in Upper Egypt from 30 to 35 feet, at Cairo 23 to 24 feet, and in the seaward part of the delta about 4 feet. The Ganges and its adjuncts begin to rise every April, and continue doing so until the plains are converted into a vast lake 32 feet deep. In other rivers sudden and heavy rains occurring at irregular intervals swell the usual volume of water and give rise to floods, freshets or "spates." This is markedly the case with the rivers of Western Europe. Thus the Rhone rises 11½ feet at Lyons and 23 feet at Avignon; the Saône from 20 to 24½ feet. In the middle of March 1876, the Seine rose 20 feet at Paris, the Oise 17 feet near Compiègne, the Marne 14 feet at Damery. The Ardèche at Gournier exceeded a rise of 69 feet during the inundations of 1827. The causes of floods, not only as regards meteorological conditions, but in respect to the geological structure of the ground in which the floods are produced, merit the careful attention of the geological student. He may occasionally observe that, other things being equal, the volume of a flood is less in proportion to the permeability of a hydrographic basin and the consequent ease with which rain can sink beneath the surface.

Were rivers entirely dependent upon direct supplies of rain, they would only flow in rainy seasons and disappear in drought. This does not happen, because they derive much of their water not directly from rain, but indirectly through the intermediate agency of springs. Hence they continue to flow even in very dry weather, because, though the superficial supplies have been exhausted, the underground sources still continue available. In a long drought, however, the latter begin to fail, the surface springs ceasing first, and gradually drying up in their order of depth, until at last only deep-seated springs furnish a perhaps daily diminishing quantity of water. Though it is a matter of great economic as well as scientific interest to know how long any river would continue to yield a certain amount of water during a prolonged drought, no rule seems

possible for a generally applicable calculation, every area having its own peculiarities of underground drainage. The river Wandle, for instance, drains an area of 51 square miles of the Chalk Downs in the south-east of England. For eighteen months, from May 1858 to October 1859, as tested by gauging, there was very little absorption of rainfall over the drainage basin, and yet the minimum recorded flow of the Wandle was 10,000,000 gallons a day, which represents not more than ·4090 inch of rain absorbed on the 51 square miles of chalk. The rock is so saturated that it can continue to supply a large yield of water for eighteen months after it has ceased to receive supplies from the surface, or at least has received only very much diminished supplies.[1]

II. Discharge.—What proportion of the total rainfall is discharged by rivers is another question of great geological and industrial interest. From the very moment that water takes visible form, as mist, cloud, dew, rain, snow, or hail, it is subject to evaporation. When it reaches the ground, or flows off into brooks, rivers, lakes, or the sea, it undergoes continual diminution from the same cause. Hence in regions where rivers receive no tributaries, they grow smaller in volume as they move onward, till in dry hot climates they even disappear. Apart from temperature, the amount of evaporation is largely regulated by the nature of the surface from which it takes place, one soil or rock differing from another, and all of them probably from a surface of water. Full and detailed observations are still wanting for determining the relation of evaporation to rainfall and river discharge.[2] During severe storms of rain, the water discharged over the land to a very large extent finds its way at once into brooks and rivers, by which it reaches the sea. Mr. David Stevenson remarks that, according to different observations, the amount carried off in floods varies from 1 to 100 cubic feet per minute per acre.[3] In estimating and comparing, therefore, the ratios between rainfall and river discharge in different regions, regard must be had to the nature of the rainfall, whether it is crowded into a rainy season or diffused over the year. Thus though floods cannot be deemed exceptional phenomena, forming as they do

[1] Lucas, *Horizontal Wells*, London, 1874, pp. 40, 41. See also Braithwaite, "On the Rise and Fall of the Wandle," *Minutes Proc. Inst. C.E.*, xx.

[2] In the present state of our information it seems almost useless to state any of the results already obtained, so widely discrepant and irreconcilable are they. In some cases the evaporation is given as usually three times the rainfall; and that evaporation always exceeded rainfall was for many years the belief among the French hydraulic engineers. (See *Annales des Ponts et Chaussées*, 1850, p. 383.) Observations on a larger scale, and with greater precautions against the undue heating of the evaporator, have since shown, as might have been anticipated, that as a rule, save in exceptionally dry years, evaporation is lower than rainfall. As the average of ten years from 1860 to 1869, Mr. Greaves found that at Lea Bridge the evaporation from a surface of water was 20·946, while the rainfall was 25·534 (Symons's *British Rainfall* for 1869, p. 162). But we need an accumulation of observations, taken in many different situations and exposures, in different rocks and soils, and at various heights above the sea. (For a notice of a method of trying the evaporation from soil, see *British Rainfall*, 1872, p. 206.)

[3] "Reclamation and Protection of Agricultural Land," Edin., 1874, p. 15.

a part of the regular system of water circulation over the land, they do not represent the ordinary proportions between rainfall and river discharge in such a climate as that of Britain, where the rainfall is spread more or less equally throughout the year. According to Beardmore's table,[1] the Thames at Staines has a mean annual discharge of 32·40 cubic inches per minute per square mile, equal to a depth of 7·31 inches of rainfall run off, or less than a third of the total rainfall. The most carefully collected data at present available are probably those given by Humphreys and Abbot for the basin of the Mississippi and its tributaries as shown in the subjoined table:—[2]

	Ratio of Drainage to Rainfall.
Ohio River	0·24
Missouri River	0·15
Upper Mississippi River	0·24
Small tributaries	0·90
Arkansas and White River	0·15
Red River	0·20
Yazoo River	0·90
St. Francis River	0·90
Entire Mississippi, exclusive of Red River	0·25

In the Mississippi basin one fourth of the rainfall is thus discharged into the sea. The Elbe, from the beginning of July 1871 to the end of June 1872, was estimated to carry off at most a quarter of the rainfall from Bohemia.[3] The Seine at Paris appears to carry off about a third of the rainfall. In Great Britain from a fourth to a third part of the rainfall is perhaps carried out to sea by streams.[4]

In comparing also the discharges of different rivers regard should be paid to the influence of geological structure, and particularly of the permeability or impermeability of the rocks as regulating the supply of water to the rivers. Thus the Thames, from a catchment basin of 3670 square miles and with a rainfall of 27 inches, has a mean annual discharge at Kingston of 1250 millions of gallons a day, and rather more than 688 millions of gallons in summer. The Severn, on the other hand, which gathers its supplies mainly from the hard, impervious slate rocks of Wales, has a drainage area above Gloucester of 3890 square miles, with an average rainfall of probably not less than 40 inches. Yet its summer discharge does not amount to 298 millions of gallons, and its minimum sinks as low as 100 millions of gallons, while that of the Thames in the driest season never falls below 350 millions. In the one case the water is stored

[1] "Hydrology," p. 201.

[2] "Physics and Hydraulics of the Mississippi River," Washington, 1861, p. 136.

[3] *Verhandl. Geol. Reichsanstalt*, Vienna, 1876, p. 173.

[4] In mountainous tracts having a large rainfall and a short descent to the sea, the proportion of water returned to the sea must be very much greater than this. Mr. Bateman's observations for seven years in the Loch Katrine district gave a mean annual rainfall of 87½ inches at the head of the lake, with an outflow equivalent to a depth of 81·70 inches of rain removed from the drainage basin of 71½ square miles. See a recent paper by Graeve on the quantity of water in German rivers, and on the relation between rainfall and discharge, *Der Civil-Ingenieur*, 1879, p. 591; *Nature*, xxiii. p. 94.

up within the rocks and is dispensed gradually; in the other, it in great measure runs off at once.[1]

III. Flow.—While, in obedience to the law of gravitation, a river always flows from higher to lower levels, great variations in the rate and character of its motion are caused by inequalities in the angle of slope of its channel. A vertical or steeply inclined face of rock originates a waterfall; a rocky declivity in the channel gives rise to rapids; a flat plain allows the stream to linger with a scarcely visible current; while a lake renders the flow nearly or altogether imperceptible. Thus the rate of flow is regulated in the main by the angle of inclination and form of the channel, but partly also by the volume of water, an increase of volume in a narrow channel increasing the rate of motion even without an increase of slope.

The course of a great river may be divided into three parts:—1. *The Mountain Track,*—where, amidst clouds or snows, it takes its rise as a mere brook, and, fed by innumerable similar torrents, dashes rapidly down the steep sides of the mountains, leaping from crag to crag in endless cascades, and growing every moment in volume, until it enters lower ground. 2. *The Valley Track.*—The river now flows through lower hills or undulations, and is found at one time in a wide fertile valley, then in a dark gorge, now falling headlong in a cataract, now expanding into a broad lake. This is the part of its career where it assumes the most varied aspects, and receives the largest tributaries. 3. *The Plain Track.*—Having quitted the undulating region the river finally emerges upon broad plains, probably wholly, or in great part, composed of alluvial formations deposited by its own waters. Here winding sluggishly in wide curves, it eventually perhaps bifurcates, as it approaches the sea and spreads through its delta, enclosing tracts of flat meadow or marsh, and finally, amid banks of mud and sand, passing out into the great ocean. In Europe the Rhine, Rhone, and Danube; in Asia the Ganges and Indus; in America the Mississippi and Amazon; in Africa the Nile, illustrate this typical course of a great river.

If we draw a longitudinal section of the course of any such river from its source, or from the highest peaks around that source to its mouth at the sea, we find that the line at first curves steeply from the mountain crests down into the valleys, but grows less and less inclined through the middle portion, until it finally can hardly be distinguished from a horizontal line. Though characteristic of great rivers, this feature is not confined to their courses, but belongs to the architecture of the continents.

It is evident that a river must flow, on the whole, fastest in the first portion of its course, and slowest in the last. The common method of comparing the fall or slope of rivers is to divide the difference of height between their source and the sea-level by their length, so as to give the declivity per mile. This mode, however, often fails to bring out the real resemblances and differences of rivers,

[1] Prestwich, *Q. J. Geol. Soc.* xxviii. p. lxv.

even in regard to their angle of slope. For example, two streams rising at a height of 1000 feet, and flowing 100 miles to the sea, would each have an average slope of 10 feet per mile; yet they might be wholly unlike each other, one making its descent almost entirely in the first or mountain part of its course, and lazily winding for most of its way through a vast low plain; the other toiling through the mountains, then keeping among hills and table-lands, so as to form on the whole a tolerably equable and rapid flow. The great rivers of the globe have probably a less average slope than 2 feet per mile. The Missouri has a descent of 28 inches per mile. The average slope of the channel of the Thames is 21 inches per mile; of the Shannon about 11 inches per mile, but between Killaloe and Limerick about 6½ feet per mile; of the Nile, below Cairo, 3·25 to 5·5 inches per mile; of the Doubs and Rhone, from Besançon to the Mediterranean, 24·18 inches per mile; of the Volga from its source to the sea, a little more than 3 inches per mile. Higher angles of descent are those of torrents, as the Arve, with a slope of 1 in 616 at Chamounix, and the Durance, whose angle varies from 1 in 467 to 1 in 208. The slope of a navigable river ought hardly to exceed 10 inches per mile, or 1 in 6336.[1]

But not only does the rate of flow of a river vary at different parts of its course, it is not the same in every part of the cross-section of the river taken at any given point. The river channel (*a a*, Fig. 106) supports a succession of layers of water (*b*, *c*, *d*), moving with different velocities, the greatest movement being at the centre (*d*), and the least in the layer which lies directly on the channel. At the same vertical depth, therefore, the velocity is greater in proportion as the point approaches the centre of the stream. The water next the sides and bottom being retarded by friction against the channel, moves less rapidly than the layers (*b b*, *c c*) towards the centre (*d*). The central piers of a bridge have thus a greater velocity of river current to bear than those at the banks. It follows that whatever tends to diminish the friction of the moving current will increase its rate of flow. The same body of water, other conditions being equal, will move faster through a narrow gorge with steep smooth walls than over a broad rough rocky bed. For the same reason, when two streams join, their united current, having in many cases a channel not much larger than that of one of the single streams, flows faster, because the water encounters now the friction of only one channel. The average rate of flow is much less than might be supposed, even in what are termed swift rivers. A moderate current is about 1¼ mile in the hour; even that of a torrent does not exceed 18 or 20 miles in the hour. Mr. D. Steven-

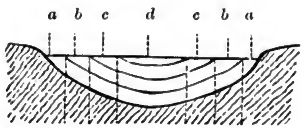

FIG. 106.—CROSS SECTION OF A RIVER.

[1] D. Stevenson, "Canal and River Engineering," p. 224.

son states that the velocity of such rivers as the Thames, the Tay, or the Clyde may be found to vary from about one mile per hour as a minimum to about three miles per hour as a maximum velocity.[1]

It may be remarked, in concluding this part of the subject, that elevations and depressions of land must have a powerful influence upon the slope of rivers. The upraising of the axis of a country, by increasing the slope, augments the rate of flow, which, on the contrary, is diminished by a depression of the axis or by an elevation of the maritime regions.

IV. Geological Action.—Like all other forms of moving water, streams have both a *chemical* and *mechanical* action. The latter receives most attention, as it undoubtedly is the more important; but the former ought not to be omitted in any survey of the general waste of the earth's surface.

i. Chemical.—The water of rivers must possess the powers of a chemical solvent like rain and springs, though its actual work in this respect can be less easily measured, seeing that river water is directly derived from rain and springs, and necessarily contains in solution mineral substances supplied to it by them. Nevertheless, that streams dissolve chemically the rocks of their channels can be strikingly seen in limestone districts, where the base of the cliffs of river ravines may be found eaten away into tunnels, arches, and overhanging projections, presenting in their smooth surfaces a great contrast to the angular jointed faces of the same rock where exposed to the influence only of the weather on the higher parts of the cliff. Daubrée endeavoured to illustrate the chemical action of rivers upon their transported pebbles by exposing angular fragments of felspar to prolonged friction in revolving cylinders of sandstone containing distilled water. He found that they underwent considerable decomposition, as was shown by the presence of silica of potash, rendering the water alkaline. Three kilogrammes of felspar fragments made to revolve in an iron cylinder for a period of 192 hours, which was equal to a journey of 460 kilometres (287 miles), yielded 2·720 kilogrammes of mud, while the five litres of water in which they were kept moving contained 12·60 grammes of potash or 2·52 grammes per litre.[2]

The mineral matter held in solution in river-water is, doubtless, partly derived from this mechanical trituration of rocks and detritus; for Daubrée's experiments show that minerals which resist the action of acid may be slowly decomposed by mere mechanical trituration, such as takes place along the bed of a river. But in sluggish streams the main supply of mineral solution is doubtless furnished by springs.

The proportion of mineral matter in river-water varies with the season, even for the same stream. It reaches its maximum when the water is mainly derived from springs, as in very dry weather

[1] "Reclamation of Land," p. 18.
[2] "Géologie Expérimentale," p. 271.

and in a frosty winter; it attains its minimum in rainy seasons and after rain.[1] Its amount and composition depend upon the nature of the rocks forming the drainage-basin. Where these are on the whole impervious the water runs off with comparatively slight abstraction of mineral ingredients; but where they are permeable the water, in sinking through them and rising again in springs, dissolves their substance and carries it into the rivers. The composition of the river waters of Western Europe is well shown by numerous analyses. The substances held in solution include variable proportions of the atmospheric gases, carbonates of lime, magnesia, soda, iron, and ammonia; silica; peroxides of iron and manganese; alumina; sulphates of lime, magnesia, potash, and soda; chlorides of sodium, potassium, calcium, and magnesium; silicate of potash; nitrates; phosphoric acid; and organic matter. The minimum proportion of mineral matter among the analyses collected by Bischof was 2·61 in 100,000 parts of water in the Möll, near Heiligenblut—a mountain stream 3800 feet above the sea, flowing from the Pasterzen glacier over crystalline schists. On the other hand, as much as 54·5 parts in the 100,000 were obtained in the waters of the Beuvronne, a tributary of the Loire above Tours. The average of the whole of these analyses is about 21 parts of mineral matter in 100,000 of water, whereof carbonate of lime usually forms the half, its mean quantity being 11·34.[2] Bischof calculated that, assuming the mean quantity of carbonate of lime in the Rhine to be 9·46 in 100,000 of water, which is the proportion ascertained at Bonn, enough of this substance is carried into the sea by this river for the annual formation of three hundred and thirty-two thousand millions of oyster shells of the usual size. The mineral next in abundance is sulphate of lime, which in some rivers constitutes nearly half of the dissolved mineral matter. Less in amount are sodium chloride, magnesium carbonate and sulphate, and silica. Of the last named, a percentage amounting to 4·88 parts in 100,000 of water has been found in the Rhine, near Strasburg. (See p. 453.) The largest amount of alumina was 0·71 in the Loire, near Orleans. The proportion of mineral matter in the Thames, near London, amounts to about 33 parts in 100,000 of water.[3]

It requires some reflection properly to appreciate the amount of solid mineral matter which is every year carried in solution from the rocks of the land and diffused by rivers into the sea. Accurate measurements of the amount of material so transported are still much required. The Thames carries past Kingston 19 grains of mineral salts in every gallon, or 1502 tons every twenty-four hours, or 548,230 tons every year. Of this quantity about two-thirds

[1] Roth, *op. cit.* i. p. 454.
[2] Bischof, "Chem. Geol." i. chap. v. More recently another similar collection of analyses, chiefly of European rivers, has been published by Roth, the mean of thirty-eight of which gives a proportion of 19·983 in 100,000 parts of water. *Op. cit.* p. 456.
[3] Bischof, *op. et loc. cit.*; Roth, *op. cit.* i. p. 454. For composition of British river-water, see "Rivers Pollution Commission Report."

consist of carbonate of lime, the rest being chiefly sulphate of lime, with minor proportions of the other ordinary salts of river-water. Mr. Prestwich estimates that the quantity of carbonate of lime removed from the limestone areas of the Thames basin amounts to 140 tons annually from every square mile. This quantity, assuming a ton of chalk to measure 15 cubic feet, is equal to a loss of $\frac{9}{100}$ of an inch from each square mile in a century or one foot in 13200 years.[1] According to monthly observations and estimates made in the year 1866 at Lobositz near the exit of the Elbe from its Bohemian basin, this river may be regarded as carrying every year out of Bohemia from an area of 880 square German miles, or, in round numbers, 20,000 English square miles, 6,000,000,000 cubic metres of water containing 622,680,000 kilogrammes of dissolved and 547,140,000 of suspended matter, or a total of 1169 millions of kilogrammes. Of this total 978 millions of kilogrammes consist of fixed and 192 millions of volatile (chiefly organic) matter. The proportions of some of the ingredients most important in agriculture were estimated as follows. In the yearly discharge of the Elbe there are carried out of Bohemia: lime, 140,380,000 kilogrammes; magnesia, 28,130,000; potash, 54,520,000; soda, 39,600,000; chloride of sodium, 25,320,000; sulphuric acid, 45,690,000; phosphoric acid, 1,500,000.[2]

Mr. T. Mellard Reade has estimated that a total of 8,370,630 tons of solids in solution is every year removed by running water from the rocks of England and Wales, which is equivalent to a general lowering of the surface of the country from that cause alone at the rate of ·0077 of a foot in a century, or one foot in 12,978 years. The same writer computes the annual discharge of solids in solution by the Rhine to be equal to 92·3 tons per square mile, that of the Rhone at Avignon 232 tons per square mile, and that of the Danube at 72·7 tons per square mile; and he supposes that on an average over the whole world there may be every year dissolved by rain about 100 tons of rocky matter per English square mile of surface.[3]

If the average proportion of mineral matter in solution in river-water be taken as 2 parts in every 10,000 by weight, then it is obvious that in every 5000 years the rivers of the globe must carry to the sea their own weight of dissolved rock.

ii. Mechanical.—The mechanical work of rivers is threefold:—(1) to transport mud, sand, gravel, or blocks of stone from higher to lower levels; (2) to use these loose materials in eroding their channels; and (3) to deposit these materials where possible, and thus to make new geological formations.

[1] Prestwich, *Q. J. Geol. Soc.* xxviii. p. lxvii.

[2] Breitenlohner, *Verhand. Geol. Reichsanst.*, Vienna, 1876, p. 172. Taking the 978,000,000 kilogrammes to be mineral matter in solution and suspension, this is equal to an annual loss of about 48 tons per English square mile. But it includes all the materials discharged by the drainage of an abundant population.

[3] Address, *Liverpool Geol. Soc.* 1877.

1. *Transporting Power.*[1]—One of the distinctions of river water, as compared with that of springs, is that, as a rule, it is less transparent, in other words, contains more or less mineral matter in suspension. A sudden heavy shower or a season of wet weather suffices to render turbid a river which was previously clear. The mud is washed into the main streams by rain and brooks, but is partly produced by the abrasion of the water-channels through the operations of the streams themselves. The channels of the mountain tributaries of a river are choked with large fragments of rock disengaged from cliffs and crags on either side. Traced downwards the blocks become gradually smaller and more rounded. They are ground against each other and upon the rocky sides and bottom of the channel, getting more and more reduced as they descend, and at the same time abrading the rocks over or against which they are driven. Of the detritus thus produced, the finer portions are carried in suspension, and impart the characteristic turbidity to rivers; the coarser sand and gravel are driven along the river bottom.[2]

The presence of a moving stratum of coarse detritus on the bed of a brook or river may be detected in transit, for though invisible beneath the overlying discoloured water, the stones of which it is composed may be heard knocking against each other as the current sweeps them onward. Above Bonn, and again a little below the Lurelei Rock, while drifting down the Rhine, the observer by laying his ear close to the bottom of the open boat, may hear the harsh grating of the gravel stones over each other as the current pushes them onwards along the bottom. On the Moselle also, between Cochem and Coblentz, the same fact may be noticed.

The transporting capacity of a stream depends (*a*) on the volume and velocity of the current, and (*b*) on the size, shape, and specific gravity of the sediment. (*a*) According to the calculations of Hopkins,[3] the capacity of transport increases as the sixth power of the velocity of the current; thus the motive power of the current is increased 64 times by the doubling of the velocity, 729 times by trebling, and 4096 times by quadrupling it. Mr. David Stevenson[4]

[1] On the abrading and transporting power of water, see Login, *Nature*, i. pp. 629, 654; ii. p. 72.

[2] These operations of running water may be studied with great advantage on a small scale where brooks descend from high grounds into valleys, rivers, or lakes. A single flood suffices for the transport of thousands of tons of stones, gravel, sand, and mud, even by a small streamlet. At Lybster, for example, on the coast of Caithness, as the author was informed by Mr. Thomas Stevenson, C.E., a small streamlet carries down annually into a harbour, which has there been made, between 400 and 500 cubic yards of gravel and sand. A weir or dam has been constructed to protect the harbour from the inroad of the coarser sediment, and this is cleaned out regularly every summer. But by far the greater portion of the fine silt is no doubt swept out into the North Sea. The erection of the artificial barrier, by arresting the seaward course of the gravel, reveals to us what must be the normal state of this stream and of similar streams descending from maritime hills. The area drained by the stream is about four square miles; consequently the amount of loss of surface, which is represented by the coarse gravel and sand alone, is $\frac{1}{1500}$ of a foot *per annum*.

[3] *Q. J. Geol. Soc.* viii. p. xxvii.

[4] "Canal and River Engineering," p. 315.

gives the subjoined table of the power of transport of different velocities of river currents:—

In. per Second.		Mile per Hour.	
3	=	0·170	will just begin to work on fine clay.
6	=	0·340	will lift fine sand.
8	=	0·4545	will lift sand as coarse as linseed.
12	=	0·6819	will sweep along fine gravel.
24	=	1·3638	will roll along rounded pebbles 1 inch in diameter.
36	=	2·045	will sweep along slippery angular stones of the size of an egg.

It is not the surface velocity, nor even the mean velocity, of a river which can be taken as the measure of its power of transport, but the bottom velocity—that is, the rate at which the stream overcomes the friction of its channel. (*b*) The average specific gravity of the stones in a river ranges between two and three times that of pure fresh water; hence these stones when borne along by the river lose from a half to a third of their weight in air. Huge blocks which could not be moved by the same amount of energy applied to them on dry ground are swept along when they have found their way into a strong river current. The shape of the fragments greatly affects their portability, when they are too large and heavy to be carried in mechanical suspension. Rounded stones are of course most easily transported; flat and angular ones are moved with comparative difficulty. (See p. 372.)

Besides inorganic sediment, rivers sweep seaward the remains of land animals and vegetation. The great rafts of the Mississippi and its tributaries are signal examples of this part of river action. The Atchafalaya has been so obstructed by drift-wood as to be fordable like dry land, and the Red River for more than a hundred miles flows under a matted cover of dead and living vegetation. The Amazon, Ganges, and other tropical rivers furnish abundant examples of the transport of a terrestrial fauna and flora to the sea.

Besides their ordinary powers of transport, rivers gain at times considerable additional force from several causes. Those liable to sudden and heavy falls of rain acquire by flooding an enormous increase of transporting and excavating power. More work may thus be done by a stream in a day than could be accomplished by it during years of its ordinary condition.[1] Another cause of sudden increase in river-action is provided when, from landslips formed by earthquakes, by the undermining influence of springs, or otherwise, a stream is temporarily dammed back, and the barrier subsequently gives way. The bursting out of the arrested waters produces great destruction in the valley. Blocks as big as houses may be set in motion, and carried down for considerable distances. Again, the transporting power of rivers may be greatly augmented by frost (see *postea*, p. 401). Ice forming along the banks or on the bottom en-

[1] The extent to which heavy rains can alter the usual characters of rivers is forcibly exemplified in the graphic account of "The Morayshire Floods," by the late Sir T. Dick Lauder. In the year 1829 the rivers of that region rose 10, 18, and in one case even 50 feet above their common summer level, producing almost incredible havoc.

closes gravel, sand, and even blocks of rock, which, when thaw comes, are lifted up and carried down the stream. The rivers of northern Russia and Siberia, flowing from south to north, have the ice thawed in their higher courses before it breaks up farther down. Much disaster is sometimes caused by the piling up of the ice, and then by the bursting of the impeded river through the temporary ice-barrier. In another way ice sometimes vastly increases the destructive powers of small streams, where avalanches or an advancing glacier cross a valley and pond back its drainage. The valley of the Dranse, in Switzerland, has several times suffered from this cause. In 1818 the glacier barrier extended across the valley for more than half a mile, with a breadth of 600 and a height of 400 feet. The waters above the ice-dam accumulated into a lake containing 800,000,000 cubic feet. By a tunnel driven through the ice, the water was drawn off without desolating the plains below.

The amount of sediment borne downwards by a river is not necessarily determined by the carrying power of the current. The swiftest streams are not always the muddiest. The proportion of sediment is partly dependent upon the hardness or softness of the rocks of the channel, the number of tributaries, the nature and slope of the ground forming the drainage basin, the amount and distribution of the rainfall, the size of the glaciers (where such exist) at the sources of the river, &c. A rainfall spread with some uniformity throughout the year may not sensibly darken the rivers with mud, but the same amount of fall crowded into a few days or weeks may be the means of sweeping a vast amount of earth into the rivers, and sending them down in a greatly discoloured state to the sea. Thus the rivers of India, swollen during the rainy season (by sometimes a rainfall 25 inches in 40 hours, as at the time of the destructive land-slip at Naini Tal in September 1880), become rolling currents of mud. In his journeys through equatorial Africa, Livingstone came upon rivers which appear usually to consist more of sand than of water. He describes the Zingesi as "a sand rivulet in flood, 60 or 70 yards wide, and waist-deep. Like all these sand-rivers, it is for the most part dry; but, by digging down a few feet, water is to be found which is percolating along the bed on a stratum of clay. In trying to ford it," he remarks, "I felt thousands of particles of coarse sand striking my legs, which gave me the idea that the amount of matter removed by every freshet must be very great. . . . These sand rivers remove vast masses of disintegrated rock before it is fine enough to form soil. In most rivers where much wearing is going on, a person diving to the bottom may hear literally thousands of stones knocking against each other."

The amount of mineral matter transported by rivers can be estimated by examining their waters at different periods and places, and determining their solid contents. A complete analysis should take into account what is chemically dissolved, what is mechanically suspended, and what is driven or pushed along the bottom. We have

already dealt with the chemically dissolved ingredients. In determinations of the mechanically mixed constituents of river water, it is most advantageous to obtain the proportion first by weight, and then from its average specific gravity to estimate its bulk as an ingredient in the water. According to experiments made upon the water of the Rhone at Lyons, in 1844, the proportion of earthy matter held in suspension was by weight $\frac{1}{17000}$. Earlier in the century the results of similar experiments at Arles gave $\frac{1}{7000}$ as the proportion when the river was low, $\frac{1}{230}$ during floods, and $\frac{1}{2000}$ in the mean state of the river. The greatest recorded quantity is $\frac{1}{45}$ by weight, which was found "when the river was two-thirds up with a mean velocity of probably about 8 feet per second."[1] Lombardini gives $\frac{1}{300}$ as the proportion by volume of the sediment in the water of the Po. In the Vistula, according to Spittell, the proportion by volume reaches a maximum of $\frac{1}{48}$.[2] The Rhine, according to Hartsoeker, contains $\frac{1}{100}$ by volume as it passes through Holland, while at Bonn the experiments of L. Horner gave a proportion of only $\frac{1}{16000}$ by volume.[3] Stiefensand found that, after a sudden flooding, the water of the Rhine at Uerdingen contained $\frac{1}{1282}$ by weight. Bischof measured the quantity of sediment in the same river at Bonn during a turbid state of the water, and found the proportion $\frac{1}{4878}$ by weight, while at another time, after several weeks of continuous dry weather, and when the water had become clear and blue, he detected only $\frac{1}{37800}$.[4] In the Maes, according to the experiments of Chandellon, the maximum of sediment in suspension in the month of December 1849 was $\frac{1}{2100}$, the minimum $\frac{1}{71420}$, and the mean $\frac{1}{10000}$.[5] In the Elbe, at Hamburg, the proportion of mineral matter in suspension and solution has been found by experiment to average about $\frac{1}{7400}$. The Danube, at Vienna, yielded to Bischof about $\frac{1}{4200}$ of suspended and dissolved matter.[6] The Durance, in floods, contains $\frac{1}{48}$ of suspended mud, and its annual average proportion is less than $\frac{1}{1000}$.[7] The Garonne is estimated to contain perhaps $\frac{1}{100}$.[8] The observations of Mr. Everest upon the water of the Ganges show that, during the four months of flood in that river, the proportion of earthy matter is $\frac{1}{428}$ by weight, or $\frac{1}{856}$ by volume; and that the mean average for the year is $\frac{1}{510}$ by weight, or $\frac{1}{1021}$ by volume.[9] According to Mr. Login, the waters of the Irrawaddy contain $\frac{1}{1700}$ by weight of sediment during floods, and $\frac{1}{5725}$ during a low state of the river.[10] In the

[1] Humphreys and Abbot, "Report upon the Physics and Hydraulics of the Mississippi," 1861, p. 147.

[2] *Ibid.* p. 148.

[3] *Edin. New Phil. Journ.* xviii. p. 102.

[4] "Chemical Geology," i. p. 122.

[5] *Annales des Travaux publics de Belgique*, ix. 204.

[6] *Op. cit.* 130. More recent observations by Sir Charles Hartley show that the mean proportion of sediment by weight in the Danube water for the ten years from 1862 to 1871 was $\frac{1}{[illegible]}$, or (at specific gravity 1·9) $\frac{1}{[illegible]}$ by volume.

[7] Payen cited by E. Réclus, "La Terre," tome i. p. 537.

[8] Baumgarten cited by Réclus, *op. cit.*

[9] *Journ. Asiatic Society of Calcutta*, March, 1832.

[10] *Proc. Roy. Soc. Edin.* 1857.

Yang-tse the proportion of sediment by weight is estimated by Mr. H. B. Guppy at $\frac{1}{2188}$,[1] but according to Dr. A. Woeikof this estimate is much under the truth.

The most extensive and accurate determinations upon this subject yet made, are those of the United States Government upon the physics and hydraulics of the Mississippi river. As the mean of many observations carried on continuously at different parts of the river for months together, Humphreys and Abbot, the engineers charged with the investigation, found that the average proportion of sediment contained in the water of the Mississippi is $\frac{1}{1500}$ by weight, or $\frac{1}{2900}$ by volume.[2] But besides the matter held in suspension, they observed that a large amount of coarse detritus is constantly being pushed along the bottom of the river. They estimated that this moving stratum carries every year into the Gulf of Mexico about 750,000,000 cubic feet of sand, earth, and gravel. Their observations led them to conclude that the annual discharge of water by the Mississippi is 19,500,000,000,000 cubic feet, and consequently, that the weight of mud annually carried into the sea by this river must reach the sum of 812,500,000,000 pounds. Taking the total annual contributions of earthy matter, whether in suspension or moving along the bottom, they found them to equal a prism 268 feet in height with a base of one square mile.

The value of these data to the geologist consists mainly in the fact that they furnish him with an approximate measurement of the rate at which the surface of the land is lowered by subaerial waste. This subject is discussed at p. 441.

2. *Excavating Power.*—It was a prominent part of the teaching of Hutton and Playfair, that rivers have excavated the channels in which they flow. Experience in all parts of the world has confirmed this doctrine. The erosive work of running water depends for its rate and character upon (*a*) the friction of the detritus driven by the current against the sides and bottom of a watercourse, modified by (*b*) the geological structure of the ground.

(*a*) Driven downward by the descending water of a river, the loose grains and stones are rubbed against each other, as well as upon the rocky bed, until they are reduced to fine sand and mud, and the sides and bottom of the channel are smoothed, widened, and deepened. The familiar effect of running water upon fragments of rock, in reducing them to rounded pebbles, is expressed by the common phrase "water-worn." A stream which descends from high rocky ground may be compared to a grinding mill; large boulders and angular blocks of rock, disengaged by frosts, springs, and general atmospheric waste, fall into its upper end; fine sand and silt are discharged into the sea. In the series of experiments already referred to, Daubrée, using fragments of granite and quartz, caused them to slide over each other in a hollow cylinder partially filled with

[1] *Nature*, xxii. p. 486, xxiii. p. 9.
[2] *Report*, p. 148. The specific gravity of the silt of the Mississippi is given as 1·9.

water, and rotating on its axis with a mean velocity of 0·80 to 1 metre in a second. He found that after the first 25 kilometres (about 15½ English miles) the angular fragments of granite had lost $\frac{4}{10}$ of their weight, while in the same distance fragments already well rounded had not lost more than $\frac{1}{100}$ to $\frac{1}{400}$. The fragments rounded by this journey of 25 kilometres in a cylinder could not be distinguished either in form or in general aspect from the natural detritus of a river-bed. A second product of these experiments was an extremely fine impalpable mud which remained suspended in the water several days after the cessation of the movement. During the production of this fine sediment, the water, even though cold, was found after a day or two to have acted chemically upon the granite fragments. After a journey of 160 kilometres, 3 kilogrammes (about 6½ lb. avoirdupois) yielded 3·3 grammes (about 50 grains) of soluble salts consisting chiefly of silicate of potash. A third product was an extremely fine angular sand consisting almost wholly of quartz, with scarcely any felspar, almost the whole of the latter mineral having passed into the state of clay. The sand grains, as they are continually pushed onward over each other upon the bottom of a river, become rounded as the larger pebbles do. But a limit is placed to this attrition by the size and specific gravity of the grains.[1] As a rule the smaller particles suffer proportionately less loss than the larger, since the friction on the bottom varies directly as the weight and therefore as the cube of the diameter, while the surface exposed to attrition varies as the square of the diameter. Mr. Sorby, in recently calling attention to this relation, remarks that a grain $\frac{1}{10}$ of an inch in diameter would be worn ten times as much as one $\frac{1}{100}$ of an inch in diameter, and a pebble 1 inch in diameter would be worn relatively more by being drifted a few hundred yards than a sand grain $\frac{1}{1000}$ of an inch in diameter would be by being drifted for a hundred miles.[2] So long as the particles are borne along in suspension they will not abrade each other, but remain angular. Daubrée found that the milky tint of the Rhine at Strasburg in the months of July and August was due, not to mud, but to a fine angular sand (with grains about $\frac{1}{20}$ millimetre in diameter) which constitutes $\frac{2}{100000}$ of the total weight of water. Yet this sand had travelled in a rapidly flowing tumultuous river from the Swiss mountains, and had been tossed over waterfalls and rapids in its journey. He ascertained also that sand with a mean diameter of grain of $\frac{1}{10}$ mm. will float in feebly agitated water; so that all sand of finer grain must remain angular. The same observer has noticed that sand composed of grains with a mean diameter of ½ mm., and carried along by water moving at a rate of 1 metre per second, gets rounded, and loses about $\frac{1}{10000}$ of its weight in every kilometre travelled.[3]

[1] "Géologie Expérimentale," p. 250, *et seq.*
[2] *Q. J. Geol. Soc.* xxxvi. p. 59.
[3] "Géologie Expérimentale," pp. 256, 258.

The effects of abrasion upon the loose materials on a river-bed are but a minor part of the erosive work performed by the stream. A layer of débris, only the upper portion of which is pushed onward by the current, protects the solid rock of the river channel, but is apt to be swept away from time to time by violent floods. Sand, gravel, and boulders, in those parts of a river channel where the current is strong enough to keep them moving along, rub down the rocky bottom over which they are driven. As the shape and declivity of the channel vary constantly from point to point, with, at the same time, frequent changes in the nature of its rocks, this erosive action is liable to continual modifications. It advances most briskly in the numerous hollows and grooves along which chiefly these loose materials travel. Wherever an eddy occurs in which gravel is kept in gyration, erosion is much increased. The stones in their movement excavate a hole in the channel, while, as they themselves are reduced to sand and mud, or are swept out by the force of the current, their places are taken by fresh stones brought down by the stream (Fig. 107). Such *pot-holes*, as they are termed, vary in size from mere cup-like depressions to huge cauldrons or pools. As they often coalesce, by the giving way of the intervening walls between two or more of them, they materially increase the deepening of the river-bed.

That a river erodes its channel by means of its transported sediment, and not by the mere friction of the water, is sometimes admirably illustrated in the course of streams filtered by one or more lakes. As the Rhone escapes from the Lake of Geneva, it sweeps with a swift clear current over ledges of rock that have not yet been very deeply eroded. The Niagara supplies a still more impressive example. Issuing from Lake Erie, and flowing through a level country for a few miles, it approaches its falls by a series of rapids. The water leaves the lake with hardly any appreciable sediment, and has too brief a journey in which to gather it before beginning to rush down the rocky channel towards the cataract. The sight of the vast body of clear water, leaping and shooting over the sheets of limestone in the rapids, is in some respects quite as striking a scene as the great falls. To a geologist it is specially instructive; for he can observe that, notwithstanding the tremendous rush of water which has been rolling over them for so many centuries, these rocks have been comparatively little abraded. The smoothed and striated surface left by the ice-sheet of the glacial period can be traced upon them almost to the water's-edge, and the flat ledges at the rapids are merely a prolongation of the ice-worn surface which passes under the banks of drift on either side. The river has hardly eroded more than a mere superficial skin of rock here since it began to flow over the glaciated limestone.

Similar evidence is offered by the St. Lawrence. This majestic river leaves Lake Ontario as pure as the waters of the lake itself. The ice-worn hummocks of gneiss at the Thousand Islands still retain

their characteristic smoothed and polished surface down to and beneath the surface of the current. In descending the river I was astonished to observe that the famous rapids of the St. Lawrence are actually hemmed in by islets and steep banks of boulder-clay and not of solid rock. So little obvious erosion does the current perform even in its tumultuous billowy descent, that a raw scar of clay betokening a recent slip is hardly to be seen. The banks are so grassed over or even covered with trees, as to prove how long they have remained undisturbed in their present condition. That very considerable local

Fig. 107.—Rocky River Channel with old Pot-holes.

destruction of these clay islands, however, has been caused by floating ice will be alluded to further on.

Mere volume and rapidity of current, therefore, will not cause much erosion of the channel of a stream unless sediment be present in the water. A succession of lakes, by detaining the sediment, must necessarily enfeeble the direct excavating power of a river On the other hand, by the disintegrating action of the atmosphere, and by the operations of springs and frosts, loose detritus as well as portions of the river-banks are continually being launched into the currents, which as they roll along are thus supplied with fresh materials for erosion.

(*b*) In the gradual excavation of a river channel a dominant influence is exercised by the lithological nature and geological structure of the rocks through which the stream flows. This influence is manifested in the form of the channel, the angle of declivity of its banks, and in the details of its erosion. On a small but instructive scale these phenomena are revealed in the operations of brooks. Thus, one of the most characteristic features of streams, whether large or small, is the tendency to wind in serpentine curves when the angle of declivity is low, and the general surface of the country tolerably level. This peculiarity may be observed in every stream which traverses a flat alluvial plain. Some slight weakness in one of its banks enables the current to cut away a portion of the bank at that point. By degrees a concavity is formed, whence the water is deflected to the opposite side, there to break with increased force against the bank. Gradually a similar concavity is cut out on that side, and so, bending alternately from one side to the other, the stream is led to describe a most sinuous course across the plain. By this process, however, while the course is greatly lengthened, the velocity of the current proportionately diminishes, until it may, before quitting the plain, become a lazy, creeping stream, in England commonly bordered with sedges and willows. A stream may eventually cut through the neck of land between two loops as at *a*, *b*, and *c*, in Fig. 108, and thus for a while shorten its channel. Instances of

FIG. 108.—MEANDERING COURSE OF A BROOK.

this nature may frequently be observed in streams flowing through alluvial land. The old deserted loops are converted, first into lakes, and by degrees into stagnant pools or bogs, until finally, by growth of vegetation and infilling of sediment by rain and wind, they become dry ground.

Although most frequent in soft alluvial plains, serpentine water-courses may also be found in solid rock if the original form of the surface was tolerably flat. The windings of the gorges of the Moselle (Fig. 109) and Rhine through the table-land between Treves, Mainz, and the Siebengebirge form a notable illustration.

Abrupt changes in the geological structure or lithological character of the rocks of a river-channel may give rise to waterfalls. In many cases this feature of river scenery has originated in lines of escarpment over which the water at first found its way, or in the same geological arrangement of hard and soft rocks by which the escarpments themselves have been produced. The occurrence of horizontal tolerably compact strata, traversed by marked lines of joint, and resting upon

softer beds, presents a structure well adapted for showing the part played by waterfalls in river erosion. The waterfall acts with special potency against the softer underlying strata at its base. These are hollowed out, and as the foundations of the superincumbent more solid beds are destroyed, slices of the latter from time to time fall off into the boiling whirlpool, where they are reduced to fragments, and carried down the stream. Thus the waterfall cuts its way backward up the stream, and as it advances, it prolongs the excavation of the ravine into which it descends. The student will frequently observe that in the recession of waterfalls and consequent erosion of ravines an important part is taken by lines of joint in the rocks; that these lines have often determined the direction of the ravine, and that the vertical walls on either side depend for their precipitousness mainly upon these divisional planes in the rock. The gorge of the Niagara affords a magnificent and remarkably simple illustration of these features of river action. At its lower end, where it enters the wide plain that extends to Lake Ontario, there stretches away, on either side of the river, a line of cliff and steep wooded bank, formed by the escarpment of the massive Niagara limestone. Back from this line of cliff, through which it issues into the lacustrine plain, the gorge of the river extends for about 7 miles, with a width of from 200 to 400 yards, and a depth of from 200 to 300 feet. At the upper end lie the world-renowned falls. The whole of this great ravine has unquestionably been cut out by the recession of the falls. When the river first began to flow, it may have found the escarpment running across its course, and may then have begun the excavation of its gorge. More probably, however, the escarpment and waterfall began to arise simultaneously and from the same geological structure. As the former grew in height, it receded from its starting point. The river-ravine likewise crept backward, but at a more rapid rate, and the result has been that while at present the cliff, worn down by atmospheric disintegration, stands at Queenstown, the ravine dug by the river extends 7 miles further inland. The waterfall will continue to cut its way back as long as the structure of the gorge continues as it is now—thick beds of limestone resting hori-

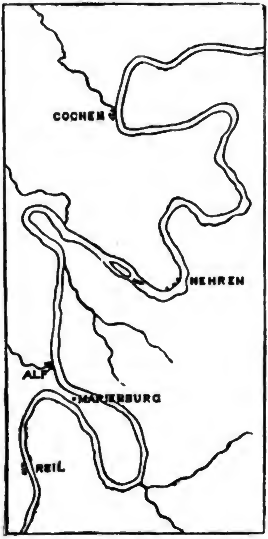

Fig. 109.—Windings of the Gorge of the Moselle above Cochem.

zontally upon soft shales (Fig. 110). The softer strata at the base are undermined, and slice after slice is cut off from the cliff over which the cataract pours. The parallel walls of this great gorge owe their direction and mural character to parallel joints of the strata. The lesser or American fall enters by the side of the ravine and falls over its lateral wall. The larger or Canadian (Horse-shoe) fall occupies the head of the ravine, and owes its form to the intersection of two sets of joints. The structure of the gorge being the same at both falls, it seems reasonable to infer that as the American fall, which appears to be diminishing in volume, has cut back only somewhere about 140 feet from the original face of the ravine, this branch of the river has, comparatively speaking, only recently begun to work. Goat Island, which now separates the two falls, is an outlier of drift resting on the limestone. It has been cut off from the rest of the ground on the right bank of the river by the branch which rejoins the main stream by the American fall. From the position of the glacial striæ it may be concluded that a great part, if not the whole of the ravine, has been excavated since the glacial period. There are indications indeed of a pre-glacial valley by which the waters of Lake Erie joined those of Ontario before the erosion of the present gorge. Bakewell, from historical notices and the testimony of old residents, inferred that the rate of recession of the falls is three feet in a year. Lyell,

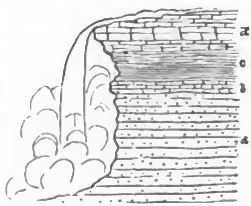

FIG. 110.—SECTION AT THE HORSE-SHOE FALLS, NIAGARA.

a, Medina Sandstone, 300 feet; *b*, Clinton Limestone and Shale, 30 feet; *c*, Niagara Shale, 80 feet; *d*, Niagara Limestone, 165 feet, of which 85 feet are visible at the fall.

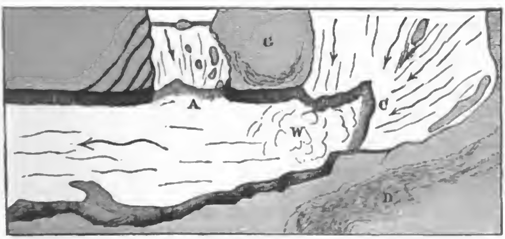

FIG. 111.—PLAN OF THE RAVINE OF NIAGARA AT THE FALLS.

A, American Fall; C, Canadian Fall; W, Whirlpool; G, Goat Island; D, Bank of Drift resting on ice-worn sheets of limestone.

on no better kind of evidence, concluded that, "the average of one foot a year would be a much more probable conjecture," and estimated

the length of time required for the excavation of the whole Niagara ravine at 35,000 years.[1]

A feature of interest in the future history of the Niagara river deserves to be noticed here. It is evident that if the structure of the gorge continued the same from the falls to Lake Erie, the recession of the falls would eventually tap the lake, and reduce it to the level of the bottom of the ravine. Successive stages in this retreat of the falls are shown in Fig. 112, by the letters *f* to *n*, and in the consequent lowering of the lake by the letters *a*, *b* to *e*. It is believed, however, that a slight inclination of the strata carries the soft underlying shale out of possible reach of the fall, which will retard indefinitely the lowering of the lake.

Fig. 112.—Section to illustrate the lowering of Lake Erie by the recession of Niagara Falls.

A waterfall may occasionally be observed to have been produced by the existence of a harder and more resisting band or barrier of rock crossing the course of the stream, as, for instance, where the rocks have been cut by an intrusive dyke or mass of basalt, or where, as in the case of the Rhine at Schaffhausen, and possibly in that of the Niagara, the stream has been diverted out of its ancient course by glacial or other deposits, so as to be forced to carve out a new channel, and rejoin its older one by a fall.[2] In these and all other cases the removal of the harder mass destroys the waterfall, which, after passing into a series of rapids, is finally lost in the general abrasion of the river-channel.

The resemblance of a deep narrow river-gorge to a rent opened in the ground by subterranean agency, has often led to a mistaken belief that such marked superficial features could only have arisen from actual violent dislocation. Even where something is conceded to the river, there is a natural tendency to assume that there must have been a line of fault and displacement as in Fig. 113, or at least a line of crack, and consequent weakness (Fig. 114). But the existence of an actual fracture is not necessary for the formation of a ravine of the first magnitude. The gorge of the Niagara, for example, has not been determined by any dislocation. Still more impressive proof of the same fact is furnished by the most marvellous river-gorges in the world—those of the Colorado region

[1] Lyell, "Travels in North America," i. p. 32; ii. p. 93. "Principles," i. p. 358. Compare Lesley's "Coal and its Topography" (1856), p. 169. On recent changes at the Falls, see Marcou, *Bull. Soc. Géol. France* (2), xxii. p. 290. The Falls of St. Anthony on the Mississippi show, according to Winchell, a rate of recession varying from 3·49 to 6·73 feet per annum, the whole recession since the discovery of the falls in 1680 to the present time being 906 feet. *Q. J. Geol. Soc.* xxxiv. p. 899.

[2] Würtenberger, *Neues Jahrb.* 1871, p. 582.

in North America. The rivers there flow in ravines thousands of feet deep and hundreds of miles long, through vast table-lands of nearly horizontal strata. The Grand Cañon (ravine) of the Colorado river is 300 miles long, and in some places more than 6000 feet in depth. In many instances there are two cañons, the upper being several miles wide, with vast lines of cliff walls and a broad plain between them, in which runs the second cañon, as another deep valley with the river winding over its bottom. The country is hardly to be crossed except by birds, so profoundly has it been trenched by these numerous gorges. Yet the whole of this excavation has been effected by the erosive action of the streams themselves.[1] Some idea of the vastness of the erosion of these plateaux may be formed from Fig. 115, and illustrations in Book VII.

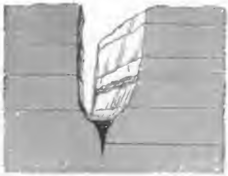

FIG. 113.—RIVER GORGE IN LINE OF FAULT.

In the excavation of a ravine, whether by the recession of a waterfall or of a series of rapids, the action of the river is more effective than that of the atmospheric agents. The sides of the ravine consequently retain their vertical character, which, where they coincide with lines of joint, is further preserved by the way in which atmospheric weathering acts along the joints. But where, from the nature of the ground or of the climate, the denuding action of rain, frost, and general weathering is more rapid than that of the river, a wider and opener valley is hollowed out, through which the river flows, and from which it carries away the materials washed into it from the surrounding slopes by rain and brooks.

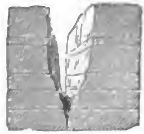

FIG. 114.—RIVER GORGE IN FISSURED STRATA.

3. *Reproductive Power.*—Every body of water which when in motion carries along sediment, drops it when at rest. The moment a current has its rapidity checked, it is deprived of some of its carrying power, and begins to lose hold upon its sediment, which tends more and more to sink and halt on the bottom the slower the motion of the water. In Fig. 116, the river in flowing from *c* to *b* has a less angle of declivity and a smaller transporting power, and will therefore have a greater tendency to throw down sediment than in descending the steeper gradient from *b* to *a*.

In the course of every brook and river there are frequent checks to the current. If these are examined, they will usually be found to be each marked by a more or less conspicuous deposit of sediment.

[1] For descriptions and figures of this remarkable region, see Ives and Newberry, "Exploration of the Colorado River of the West," 1861. J. W. Powell, "Exploration of the Colorado River of the West and its Tributaries," 1875, and *postea*, Book VII.

We may notice seven different situations in which stream-deposits or *alluvium* may be accumulated.

Fig. 115.—View of the Erosion on the San Juan, Colorado Basin (Newberry).

(*a*) At the foot of Mountain Slopes.—When a runnel or torrent descends a steep declivity it tears down the soil and rocks, cutting a gash out of the side of the mountain (Fig. 117). On reaching the more

level ground at the base of the slope the water, abruptly checked in its velocity, at once drops its coarser sediment, which gathers in a fan-shaped pile or cone ("*cone de déjection*"), with the apex pointing up the water-course. Huge accumulations of boulders and shingle may

FIG. 116.—SECTION OF PART OF A RIVER CHANNEL (*B.*).

thus be seen at the foot of such torrents,—the water flowing through them often in several channels which re-unite in the plain beyond. From the deposits of small streams every gradation of size may be

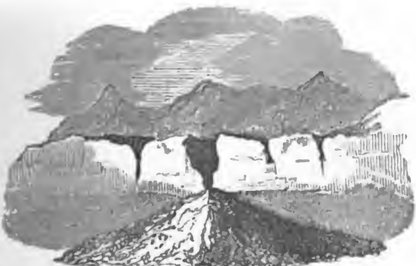

FIG. 117.—TRIBUTARY TORRENT SENDING A CONE OF DETRITUS INTO A VALLEY (*B.*).

traced up to huge fans many miles in diameter and several hundred feet thick, such as occur in the upper basin of the Indus[1] and on the flanks of the Rocky Mountains,[2] and other ranges in North America (Fig. 118).

(*b*) In River-beds.—This is characteristically shown by the accumulation of a bed of sand or shingle at the concave side of each sharp bend of a river course. While the main current is making a sweep round the opposite bank, the water lingers along the inner side of the curve and drops there its freight of loose detritus, which, when laid bare in dry weather, forms the familiar sand-bank or shingle beach. Again, when a river, well supplied with sediment, leaves mountainous ground where its course has been rapid, and enters a region of level plain, it begins to drop its burden on its bed, which is thereby heightened, till it may actually rise above the level

[1] For an interesting account of the alluvial deposits of this region, see Drew, Q. J. Geol. Soc. xxix. p. 441.

[2] See Dutton's "High Plateaux of Utah." Hayden's "Reports of the U.S. Geological and Geographical Surveys of the Territories."

of the surrounding plains as at *l* (Fig. 119). This tendency is displayed by the Adige, Reno, and Brenta, which, descending from the Alps well supplied with detritus, debouch on the plains of the Po.

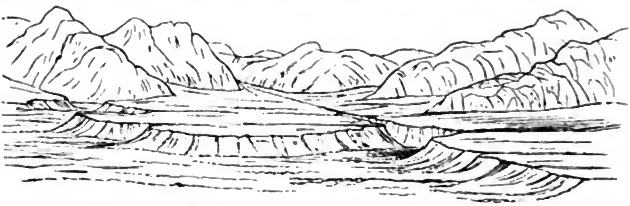

Fig. 118.—Fans of Alluvium. Madison River, Montana.

The Po itself has been quoted as an instance of a river continuing to heighten its bed, while man in self-defence heightens its embankments, until the surface of the river becomes higher than the plains on either side. It has been shown by Lombardini, however, that the bed of this river has undergone very little change for centuries; that

Fig. 119.—Section of a River Plain, showing heightening of Channel by deposit of Sediment (*B.*).

only here and there does the mean height of the Po rise above the level of the plains, being generally considerably below it, and that even in a high flood the surface of the river is scarcely ten feet above the pavement in front of the palace at Ferrara. The Po and its tributaries have been carefully embanked, so that much of the sediment of the rivers, instead of accumulating on the plains of Lombardy as it naturally would do, is carried out into the Adriatic. Hence, partly, no doubt, the remarkably rapid rate of growth of the delta of the Po. But in such cases man needs all his skill and labour to keep the banks secure. Even with his utmost efforts the river will now and then break through, sweeping down the barrier which it has itself made, as well as any additional embankments constructed by him, and carrying its flood far and wide over the plain. Left to itself, the river would incessantly shift its course, until in turn every part of the plain had been again and again traversed. It is indeed in this way that a great alluvial plain is gradually levelled and heightened.[1]

(*c*) On River-banks and Flood-plains.—As is partly implied in

[1] It is in the north of Italy that the struggle between man and nature in this department has been most persistently waged. See on this subject Lombardini, in *Ann. des Ponts et Chaussées*, 1847. Beardmore's "Tables," p. 172.

the action described in the foregoing paragraph, alluvium is laid down on the level tracts or flood-plain over which a river spreads in flood. It consists usually of fine silt, mud, earth, or sand; though close to the channel it may be partly made up of coarser materials. When a flooded river overflows, the portions of water which spread out on the plains, by losing velocity and consequently power of transport, are compelled to let fall some or all of their mud and sand. If the plains happen to be covered with woods, bushes, scrub, or tall grass, the vegetation acts the part of a sieve, and filters the muddy water, which may rejoin the main stream comparatively clear. The height of the plain is thus increased by every flood, until, partly from this cause and partly, in the case of a rapid stream, from the erosion of the channel, the plain can no longer be overspread by the river. As the channel is more and more deepened, the river continues, as before, to be liable, from inequalities in the material of its banks, sometimes of the most trifling kind, to be turned from side to side in wide curves and loops, and cuts into its old alluvium, making eventually a newer plain at a lower level. Prolonged erosion carries the channel to a still lower level, where the stream can attack the later alluvial deposit, and form a still lower and newer one. The river comes by this means to be fringed with a series of terraces, Fig. 120, the surface of each of which represents a

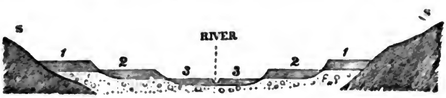

FIG. 120.—SECTION OF RIVER TERRACES.

former flood-level of the stream.[1] In Britain it is common to find three such terraces, but sometimes as many as six or seven or even more may occur. On the Seine and other rivers of the North of France there is a marked terrace at a height of 12 to 17 metres above the present water level. In North America the river-terraces exist on so grand a scale that the geologists of that country have named one of the later periods of geological history, during which those deposits were formed, the *Terrace Epoch.* The modern alluvium of the Mississippi from the mouth of the Ohio to the Gulf of Mexico covers an area of 19,450 miles, and has a breadth of from 25 to 75 miles and a depth of from 25 to 40 feet. The old alluvium of the Amazon likewise forms extensive lines of cliff for hundreds of miles, beneath which a newer platform of detritus is being formed.

In the attempt to reconstruct the history of the old river-terraces of a country, we have to consider whether they have

[1] The stages of this process in the régime of a great river are well brought out in the case of the Amazon. C. B. Brown, *Q. J. Geol. Soc.* xxxv. p. 763.

been entirely cut out of older alluvium (in which case, of course, the valleys must have been as deep as now before the formation of the terraces); whether they afford any indications of having been formed during a period of greater rainfall, when the rivers were larger than at present; whether they point to upheaval

Fig. 121.—Old Terraces on the Left Bank of the Yellowstone River, above the first Cañon. Montana.

of the interior of the country which would accelerate the erosive action of the streams, or to depression of the interior or rise of the seaward tracts, which would diminish that action and increase the deposition of alluvium. Professor Dana has connected the terraces of America with the elevation of the axis of that continent.

There can be no doubt that both in Europe and North America the rivers at a comparatively recent geological period had a much greater volume than they now possess. Their valleys are not only marked by terraces but in many cases are filled with the deep and extensive deposit known as loess. The Rhine and the Danube are both fringed for long distances by high banks composed of this deposit. Still more extensive is the loess of the Mississippi basin; it extends for hundreds of miles along the river, forming bluffs, which rise 150 feet or more above the present valley bottom. Loess is a pale yellow, calcareous, friable clay, extremely fine in texture, with little or no trace of stratification. It contains land and fresh-water shells with bones of land animals and remains of land vegetation. It has been generally supposed to have been laid down by the rivers during a period when they were swollen with muddy water derived from copious rains and melting snows. It seems, however, to shade off laterally into loess which, stretching far beyond any conceivable overflow of the rivers, must be due either to rain-wash or to that sand-drift already described (p. 322).

(*d*) In Lakes.—When a river enters a lake its current is at once checked, and its sediment begins to spread in fan-shape over the lake bottom (*c* in Fig. 122). Every tributary stream brings in its contribution of detritus. In this way a series of shoals is pushed out into the lake (Fig. 123). This phenomenon may frequently be instructively observed from a height overlooking a small lake among mountains. At the mouth of each torrent or brook lies a little tongue of its alluvium (a true *delta*), through which the streamlet winds in one or more branches before mingling its waters with those of the lake. Two streams entering a lake from opposite sides may join their alluvia so as to divide the lake into two, like the once

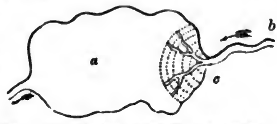

FIG. 122.—STREAMLET (*b*) ENTERING A SMALL LAKE (*a*), AND DEPOSITING A FAN OF SEDIMENT (*c*).

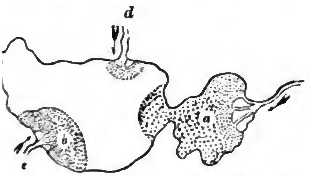

FIG. 123.—PLAN OF A LAKE ENTERED BY THREE STREAMS (*c*, *d*, *e*), EACH OF WHICH DEPOSITS A CONE OF SEDIMENT (*a*, *b*) AT ITS MOUTH.

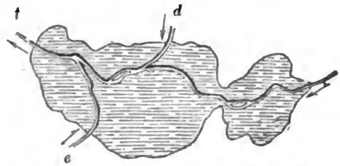

FIG. 124.—LAKE (AS IN FIG. 123) FILLED UP AND CONVERTED INTO AN ALLUVIAL PLAIN BY THE THREE STREAMS, *c*, *d*, *e*.

united lakes of Thun and Brienz at Interlaken. Or by the advance of the alluvial deposits the lake may be finally filled up altogether, as has happened in innumerable cases in all mountainous countries (Fig. 124). The rapidity of the infilling is sometimes not a little remarkable. Since the year 1714 the Kander is said to have thrown into the Lake of Thun a delta measuring 230 acres, now partly woodland, partly meadow and marsh.

In the case of a large lake whose length is great in proportion to the volume of the tributary river, the whole of the detritus may be deposited, so that, at the outflow, the river becomes as clear as when its infant waters began their course from the springs, snows, and mists of the far mountains. Thus the Rhone enters the Lake of Geneva turbid and impetuous, but escapes at Geneva as blue translucent water. Its sediment is laid down on the floor of the lake, and chiefly at the upper end, as an important delta which quite rivals that of a great river in the sea. Hence, lakes act as filters or sieves to intercept the sediment which is travelling in the rivers from the high grounds to the sea (pp. 373, 392).

(*e*) Bars and Lagoon-Barriers.—If we take a broad view of terrestrial degradation we must admit that the deposit of any

sediment on the land is only temporary; the inevitable destination of all detrital material is the floor of the sea. Most rivers which enter the sea have their mouths crossed by a bar of gravel, sand, or mud. The formation of this barrier results from the conflict between the river and the ocean. Although the muddy fresh water floats on the heavier salt water, its current is lessened, and it can no longer push along the mass of detritus at the bottom, which therefore accumulates and tends to form a bar. It has been ascertained, moreover, that, though fresh water can retain for a long while fine mud in suspension, this sediment is rapidly thrown down when the fresh is mixed with saline water. Hence, apart from the necessary loss of transporting power by the checking of the river current at the mouth, the mere mingling of a river with the sea must of itself be a cause of the deposit of sediment. (See *postea*, p. 435.) Moreover, in many cases the sea itself piles up great part of the sand and gravel of the bar. Heavy river-floods push the bar farther to sea, or even temporarily destroy it; storms from the sea, on the other hand, drive it farther up the stream.

Some of these facts in the régime of rivers have been well studied at the mouths of the Mississippi. At the South-west Pass the bar is equal in bulk to a solid mass one mile square and 490 feet thick, and advances at the rate of 338 feet each year. It is formed where the river water begins to ascend over the heavier salt-water of the gulf, and consists mainly of the sediment that is pushed along the bed of the river. A singular feature of the Mississippi bars is the formation upon them of "mud lumps." These are masses of tough clay, varying in size from mere protuberances like tree trunks, up to islands several acres in extent. They rise suddenly and attain heights of from 3 to 10, sometimes even 18 feet above the sea-level. Salt springs emitting inflammable gas rise upon them. After the lapse of a considerable time the springs cease to emit gas, and the

FIG. 125.—SHINGLE AND SAND-SPIT (*e*) AT THE MOUTH OF AN ESTUARY (*c*), ENTERED BY A RIVER, AND OPENING UPON AN EXPOSED ROCKY COAST-LINE (*B*.).

lumps are worn away by the currents of the river and the gulf. The origin of these excrescences has been attributed to the generation of carburetted hydrogen by the decomposing vegetable matter in the sediment underlying the tenacious clay of the bars.[1]

[1] Humphreys and Abbot, "Report on Mississippi River," 1861, p. 452.

Conspicuous examples of the formation of detrital bars may occasionally be observed at the mouths of narrow estuaries, as at *e* in Fig. 125. A constant struggle takes place in such situations between the tidal currents and waves which tend to heap up the bar and block the entrance to the estuary, and the scour of the river and ebb-tide which endeavours to keep the passage open.

Another remarkable illustration of the contest between alluvium-carrying streams and the land-eroding ocean is shown by the vast lines of bar or bank which stretch along the coasts both of the Old and the New World. The streams do not flow straight into

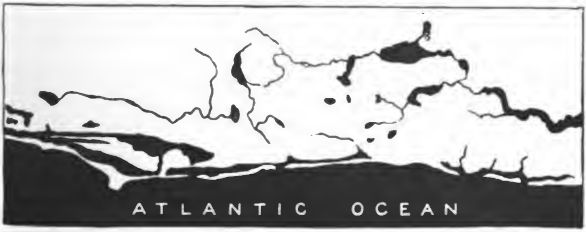

FIG. 126.—PLAN OF COAST BARS AND LAGOONS. COAST OF FLORIDA.

the sea, but run sometimes for many miles parallel to the shore-line, accumulating behind the barriers into broad and long lagoons, but eventually breaking through the barriers of alluvium and entering the sea. On a small scale examples occur on the coasts of the British Islands as at Start Bay, Devon (Fig. 127), where the slates (*e*) with their weathered surface (*d*) are flanked by a fresh water-lake (*c*), ponded back by a bar (*b*) from the sea (*a*). The lagoons of the

FIG. 127.—SECTION BAR AND LAGOON, SLAPTON POOL, START BAY, DEVON (*B*.).

Italian coast and the Kurische and Frische Haf in the Baltic, near Dantzic, are familiar examples. A conspicuous series of these alluvial bars fronts the American mainland for many hundred miles round the Gulf of Mexico and the shores of Florida, Georgia, and North Carolina (Fig. 126). A space of several hundred miles on the east coast of India is similarly bordered. É. de Beaumont, indeed, estimated that about a third of the whole of the coast-lines of the continents is fringed with such alluvial bars.[1]

On a coast-line such as that of Western Europe, subject both to powerful tidal action and to strong gales of wind, many interesting illustrations may be studied of the struggle between the rivers and the sea, as to the disposal of the sediment borne from the land. De

[1] *Leçons de Géologie pratique*, i. p. 249. In this volume some interesting examples of this kind of deposit are described.

la Beche described an example from the coast of South Wales where two streams, the Towey and Nedd (*a* and *b*, Fig. 128), enter Swansea Bay, bearing with them a considerable amount of sandy and muddy sediment. The fine mud is carried by the ebb-tide (*t t t*) into the sheltered bay between Swansea (*c*) and the Mumble Rocks (*e*), but is partly swept round this headland into the Bristol Channel. The

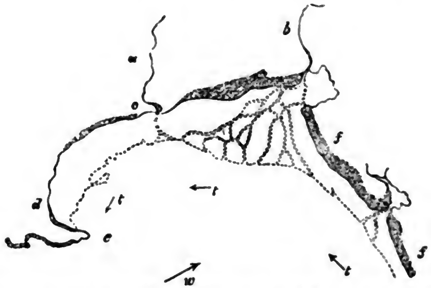

Fig. 128.—Action of Rivers, Tides, and Winds in Swansea Bay (*B.*).

coarser sandy sediment, more rapidly thrown down, is stirred up and driven shorewards by the breakers caused by the prevalent west and south-west winds (*w*). The sandy flats thereby formed are partly uncovered at low water, and being then dried by the wind, supply it with the sand which it blows inland to form the lines of sand-dunes (*ff*).[1]

(*f*) Deltas in the Sea.—The tendency of sediment to accumulate in a tongue of flat land when a river loses itself in a lake is exhibited on a far vaster scale where the great rivers of the continents enter the sea. It was to one of these maritime accumulations, that of the Nile, that the Greeks gave the name Delta, from its resemblance to their letter Δ, with the apex pointing up the river, and the base fronting the sea. This shape being the common one in all such alluvial deposits at river mouths, the term delta has become their general designation. A delta consists of successive layers of detritus, brought down from the land and spread out in the sea at the mouth of a river until they reach the surface, and then, partly by growth of vegetation and partly by flooding of the river, form a plain, of which the inner and higher portion comes eventually to be above the reach of floods. Large quantities of drift-wood are often carried down, and bodies of animals are swept off to be buried in the delta, or even to be floated out to sea. Hence, in deposits formed at the mouths of rivers, we may always expect to find terrestrial organic remains.

A delta does not necessarily form at every river-mouth, even where there is plenty of sediment. In particular, where the coast-

[1] "Geological Observer," p. 88.

line on either side is lofty, and the water deep, or where the coast is swept by powerful tidal currents, there is no delta. In some cases, too, the sediment spreads out over the sea-bottom without being allowed by the sea to build itself up into land, as happens at the mouths of some of the rivers in the north-west of France.

When a river enters upon the delta portion of its course it assumes a new character. In the previous parts of its journey it is always being augmented by tributaries; but now it begins to split up into branches, which wind to and fro through the flat alluvial land, often coalescing and thus enclosing insular spaces of all dimensions. The feeble current, no longer able to bear along all its weight of sediment, allows much of it to sink to the bottom and to gather over the tracts which are from time to time submerged. Hence many of the channels get choked up, while others are opened out in the plain, to be in turn abandoned; and thus the river restlessly shifts its channels. The seaward ends of at least the main channels grow outwards by the constant accumulation of detritus pushed into the sea, unless this growth chances to be checked by any marine current sweeping past the delta. These features are nowhere more strikingly displayed than by the great delta of the Mississippi (Fig. 129). The area of

FIG. 129.—MAP OF DELTA OF MISSISSIPPI.

this vast expanse of alluvium is given at 12,300 square miles, advancing at the rate of 262 feet yearly into the Gulf of Mexico at a point which is now 220 miles from the head of the delta.[1]

On a smaller scale the rivers of Europe furnish many excellent illustrations of delta growth. Thus the Rhine, Meuse, Sambre, Scheldt, and other rivers have formed the wide maritime plain of

[1] Humphreys and Abbot, *op. cit.*

Holland and the Netherlands. The Rhone has deposited an important delta in the Mediterranean Sea. The upper reaches of the Adriatic Sea are being so rapidly shallowed and filled up by the Po, Adige, and other streams, that Ravenna, originally built in a lagoon like Venice, is now 4 miles from the sea, and the port of Adria, so well known in ancient times as to have given its name to the Adriatic, is now 14 miles inland, while on other parts of that coast-line the breadth of land gained within the last 1800 years has been as much as 20 miles. Borings for water near Venice to a depth of 572 feet have disclosed a succession of nearly horizontal clays, sands, and lignitiferous beds. Marine shells (*Cardium, &c.*) occur in the sandy layers; the lignites and lignitiferous clays contain land vegetation and terrestrial shells (*Succinea, Pupa, Helix*), the whole succession of deposits indicating an alternation of marine and terrestrial or fresh-water conditions.[1] On the opposite side of the Italian peninsula, great additions have been made to the coast-line within the historical period. It is computed that the Tuscan rivers lay down as much as 12 million cubic yards of sediment every year within the marshes of the Maremma. The "yellow" Tiber, as it was aptly termed by the Romans, owes its colour to the abundance of the sediment which it carries to sea. It has long been adding to the coast-line at its mouth at the rate of from 12 to 13 feet per annum. The ancient harbour of Ostia is now consequently more than 3 miles inland. Its ruins are at present being excavated, but every flood of the river leaves a thick deposit of mud on the streets and on the floors of the uncovered houses. Hence it would seem that the Tiber has not only advanced its coast-line, but has raised its bed on the plains by the deposit of alluvium, so that it now overflows places which, 2000 years ago, could not have been so frequently under water.[2] In the Black Sea a great delta is rapidly growing at the mouths of the Danube. At the Kilia outlets the water is shallowing so fast that the lines of soundings of 6 feet and 30 feet are advancing into the sea at the rate of between 300 and 400 feet per annum.[3] The typical delta of the Nile has a seaward border 180 miles in length, the distance from which to the apex of the plain where the river bifurcates is 90 miles. The united delta of the Ganges and Brahmaputra (Fig. 130) covers a space of between 50,000 and 60,000 square miles, and has been bored through to a depth of 481 feet.

[1] Élie de Beaumont, "Leçons de Géologie pratique," i. p. 323. *Geol. Mag.* ix. (1872), p. 486.

[2] See an interesting article by Professor Charles Martins on the Aigues-Mortes, in *Revue des Deux Mondes*, 1874, p. 780. I accompanied the distinguished French geologist on the occasion of his visit to Ostia in the spring of 1873, and was much struck with the proofs of the rapidity of deposit in favourable situations. In the article just cited some valuable information is given regarding the progress of the delta of the Rhone in the Mediterranean. Interesting historical information as to geological changes at the mouths of the Rhine, Meuse, Elbe, Po, Rhone, and other European rivers, as well as of the Nile, will be found in Élie de Beaumont's "Leçons de Géologie pratique," vol. i. p. 253.

[3] Hartley, *Min. of Proc. Inst. Civ. Engin.* xxxvi. p. 216.

(*g*) Sea-borne Sediment.—Although more properly to be noticed under the section on the Sea, the final course of the materials worn by rains and rivers from the surface of the land may be referred to here. By far the larger part of these materials sinks to the bottom

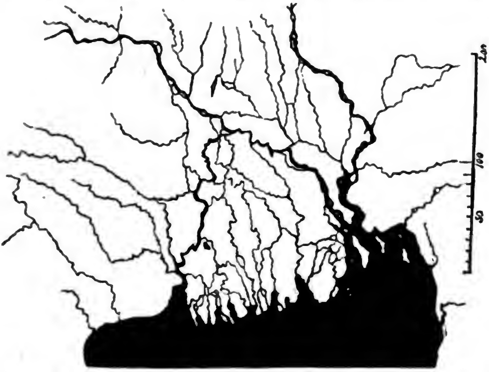

FIG. 130.—DELTA OF THE GANGES AND BRAHMAPUTRA (WITH SCALE OF MILES).

close to the land. It is only the fine mud carried in suspension in the water which is carried out to sea. The sea fronting the Amazon is discoloured for 300 miles by the mud of that river. The soundings taken by the "Challenger" brought up land-derived detritus from depths of 1500 fathoms,—200 miles or more from the nearest shores (p. 438).

§ 4. Lakes.

Depressions filled with water on the surface of the land, and known as lakes, occur abundantly in the northern parts of both hemispheres, and more sparingly, but often of large size, in warmer latitudes. They do not belong to the normal system of erosion in which running water is the prime agent, and to which the excavation of valleys and ravines must be attributed. On the contrary, they are exceptional to that system, for the constant tendency of running water is to fill them up. Their origin, therefore, must be sought among some of the other geological processes. (See Book VII.)

Lakes are conveniently classed as fresh or salt. Those which possess an outlet contain in almost all cases fresh water; those which have none are usually salt.

1. **Fresh-water Lakes.**—In the northern parts of Europe and America, lakes are prodigiously abundant on ice-worn rocky surfaces irrespective of dominant lines of drainage. They seem to be distributed as it were at random, being found now on the summits of ridges,

now on the sides of hills, and now over broad plains. They lie for the most part in rock-basins, but many of them have barriers of detritus. Their connection with the operations of the glacial period will be afterwards alluded to. In the mountainous regions of temperate and polar latitudes, lakes abound in valleys, and are connected with main drainage lines. In North America and in Equatorial Africa, vast sheets of fresh water occur in depressions of the land, and are rather inland seas than lakes.

The distribution of temperature in lakes is a question of considerable geological interest in regard to which careful measurements are much needed. The observations of Sir Robert Christison at Loch Lomond in Scotland, show that in this sheet of water, which lies 25 feet above the sea-level, with a depth of about 600 feet, and is in great measure surrounded with high hills, a tolerably constant temperature of about 42° Fahr. is found to pervade the lowest 100 feet of water. Again in the Lake of Geneva the surface temperature in autumn is 78° Fahr., while the bottom water at a depth of 950 feet was found to mark 41° 7′. The Lago Sabatino near Rome has a temperature of 77° at the surface, but one of 44° at a depth of 490 feet. Similar observations on other deep lakes in Switzerland and Northern Italy indicate the existence in all of them of a permanent mass of cold water at the bottom. The cold heavy water of the surface in winter must sink down, and as the upper layers cannot be heated by the direct rays of the sun, save to a trifling and superficial extent, the temperature of the deep parts of these basins is kept permanently low.

Geological functions.—Among the geological functions discharged by lakes the following may be noticed:

1st. Lakes equalize the temperature of the localities in which they lie, preventing it from falling as much in winter and rising as much in summer as it would otherwise do. The mean annual temperature of the surface water at the outflow of the lake of Geneva is nearly 4° warmer than that of the air.

2nd. Lakes regulate the drainage of the area below their outfall, thereby preventing or lessening the destructive effects of floods.[1]

3rd. Lakes filter river water and permit the undisturbed accumulation of new deposits, which in some modern cases may cover thousands of square miles of surface, and may attain a thickness of nearly 3000 feet (Lake Superior has an area of 32,000 square miles; Lago Maggiore is 2800 feet deep). How thoroughly lakes can filter river-water is typically displayed by the contrast between the muddy river which flows in at the head of the Lake of Geneva, and the "blue rushing of the arrowy Rhone," which escapes at the

[1] Winds, by blowing strongly down the length of a lake, sometimes considerably increase for the time being the volume of the outflow. If this takes place coincidently with a heavy rainfall, the flood of the escaping river is greatly augmented. These features are noticed in Loch Tay (D. Stevenson, "Reclamation of Land," p. 14). Hence, though, on the whole lakes tend to moderate floods in the outflowing rivers, they may, by a combination of circumstances, sometimes increase them.

foot. The mouths of small brooks entering lakes afford excellent materials for studying the behaviour of silt-bearing streams when they reach still water. Each rivulet may be observed pushing forward its delta composed of successive sloping layers of sediment (*ante* p. 384). On a shelving bank the coarser detritus may repose directly upon the solid rock of the district (Fig. 131). But as it

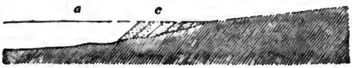

FIG. 131.—SECTION OF A DELTA-CONE PUSHED BY A BROOK INTO A LAKE.

advances into the lake it may come to rest upon some older lacustrine deposit (Fig. 132).

A river which flows through a succession of lakes cannot carry much sediment to the sea, unless it has a long course to run after it has passed the lowest lake, and receives one or more muddy tributaries. Let us suppose, for example, that in a hilly region, a

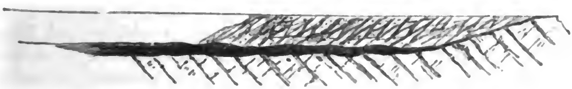

FIG. 132.—STREAM DETRITUS PUSHED FORWARD OVER A PREVIOUS LACUSTRINE SILT (*B.*).

stream passes through a series of lakes (as *a, b, c,* in Fig. 133). As the highest lake will intercept much, perhaps all, of this sediment, the next in succession will receive little or none until the first is either filled up or has been drained by the cutting of a gorge through the intervening rock at *f*. The same process will be repeated at *e* and *d* until the lakes are effaced, and their places are taken by alluvial meadows.

Besides the detrital accumulations due to the influx of streams there are some which may properly be regarded as the work of lakes

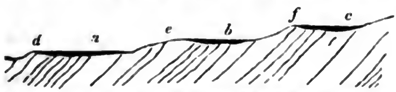

FIG. 133.—FILLING UP OF A SUCCESSION OF LAKES (*B.*).

themselves. Even on small sheets of water the eroding influence of wind waves may be observed; but on large lakes the wind throws the water into waves which almost rival those of the ocean in size and destructive power. Beaches, sand-dunes, shore-cliffs, and other familiar features of the meeting line between land and sea reappear along the margins of such great fresh-water seas as Lake Superior. Beneath the level of the water a terrace or platform is formed, the distance from shore and depth of which vary with the

energy of the waves by which it is produced. This subaqueous platform is well developed in the Lake of Geneva.

4th. Lakes serve as basins in which chemical deposits may take place. Of these, the most interesting and extensive are those of iron ore, which chiefly occur in northern latitudes (p. 174).[1]

5th. Lakes furnish an abode for a lacustrine fauna and flora, receive the remains of the plants and animals washed down from the surrounding country, and entomb these organisms in the growing deposits, so as to preserve a record of the terrestrial life of the period during which they continue. It is as receptacles of sediment and localities for the preservation of a portion of the terrestrial fauna and flora that lakes present their chief interest to a geologist. Their deposits consist of alternations of sand, silt, mud, and gravel, with occasional irregular seams of vegetable matter, and layers of calcareous marl formed from the accumulation of lacustrine shells, *Entomostraca*, &c. In lakes receiving much sediment little or no marl can accumulate during the time when sediment is being deposited. In small, clear, and not very deep lakes, on the other hand, where there is little sediment or where it only comes occasionally at intervals of flood, beds of white marl, formed entirely of organic remains, may gather on the bottom to a depth of many yards, as has happened in numerous districts of Scotland and Ireland. The fresh-water limestones and clays of some old lake basins (those of Miocene time in Auvergne and Switzerland, and of Eocene age in Wyoming, for example) cover areas occasionally hundreds of square miles in extent, and attain a thickness of hundreds, sometimes even thousands of feet.

Existing lakes are of geologically recent origin. Their disappearance is continually in progress by infilling and erosion. Besides the displacement of their water by alluvial accumulations, they are lowered and eventually drained by the cutting down of the barrier at their outlets. Where they are effaced merely by erosion it must be an excessively slow process, owing to the filtered character of the water (p. 373), but where it is performed by the retrocession of a waterfall at the head of an advancing gorge it may be relatively rapid.[2] It is usual to find in a river course a lake-like expansion of alluvial land above each gorge. These plains may be regarded as old lake-bottoms, which have been drained by the cutting out of the ravines. It is likewise common to meet with successive terraces fringing a lake and marking former levels of its waters. When we reflect upon the continued operation of the agencies which tend to efface them, the lakes now extant are seen to be necessarily of comparatively recent date. Their modes of origin are discussed in Book VII.

[1] For an elaborate paper on these lake-ores (See-erze) see Stapff, *Z. Deutsch. Geol. Ges.* xviii. pp. 86–173; also *postea* Section III. p. 462.

[2] The level of the Lake of Geneva is said to have been lowered about six and a half feet since Roman times (*Bull. Soc. Géol. France* (3), iii. p. 140); but this may be explicable by diminution in the water supply.

II. Saline Lakes, considered chemically, may be grouped as *salt lakes*, where the chief constituents are sodium and magnesium chlorides with magnesium and calcium sulphates; and *bitter lakes*, which usually are distinguished by their large percentage of sodium carbonate as well as chloride and sulphate (natron-lakes), sometimes by their proportion of borax (borax lakes). From a geological point of view they may be divided into two classes—(1) those which owe their saltness to the evaporation and concentration of the fresh water poured into them by their feeders; and (2) those which were originally parts of the ocean.

(*a*) Salt and bitter lakes of terrestrial origin are abundantly scattered over inland areas of drainage in the heart of continents, as in Utah and adjacent Territories of North America, and in the great plateau of Central Asia. These sheets of water were doubtless fresh at first, but they have progressively increased in salinity, because, though the water is evaporated, there is no escape for its dissolved salts, which consequently remain in the increasingly concentrated liquid.

The Great Salt Lake of Utah, which has now been so carefully studied by Gilbert and other geologists, may be taken as a typical example of an inland basin, formed by unequal subterranean movement that has intercepted the drainage of a large area, wherein rainfall and evaporation on the whole balance each other, and where the water becomes increasingly salt from evaporation, but is liable to fluctuations in level, according to oscillations of meteorological conditions. The present lake occupies an area of rather more than 2000 square miles, its surface being at a height of 4250 feet above the sea. It is, however, merely the shrunk remnant of a once far more extensive sheet of water to which the name of Lake Bonneville has been given by Gilbert. It is partly surrounded with mountains, along the sides of which well-defined lines of terrace mark former levels of the water. The highest of these terraces lies about 940 feet above the present surface of the lake, so that when at its greatest dimensions, this vast sheet of water must have stood at a level of about 5200 feet above the sea, and covered an area of 300 miles from north to south, and 180 miles in extreme width from east to west. It was then certainly fresh, for, having an outlet to the north, it drained into the Pacific Ocean, and in its stratified deposits an abundant lacustrine molluscan fauna has been found. According to Gilbert there are proofs that previous to the great extension of Lake Bonneville, there was a dry period, during which considerable accumulations of subaerial detritus were formed along the slopes of the mountains. A great meteorological change then took place, and the whole vast basin, not only that termed Lake Bonneville, but a second large basin, Lake Lahontan of King, lying to the west and hardly inferior in area, was gradually filled with fresh water. Again another meteorological revolution supervened and the climate once more became dry. The waters shrank back, and in so

doing, when they had sunk below the level of their outlet, began to grow increasingly saline. The decrease of the water and the increase of salinity were in direct relation to each other, until the present degree of concentration has been reached, as shown in the table (p. 398). The Great Salt Lake, at present having an extreme depth of less than 50 feet, is still subject to oscillations of level. When surveyed by the Stansbury expedition in 1849, its level was eleven feet lower than in 1877, when the Survey of the 40th Parallel

Fig. 134.—Terraces of Great Salt Lake, on the flanks of the Wahsatch Mountains.

examined the ground. From 1866, however, a slow subsidence of the lake has been in progress, consequent upon a diminution of the rainfall. Large tracts of flat land formerly under water are being laid bare. As the water recedes from them and they are exposed to the remarkably dry atmosphere of these regions, they soon become crusted with a white saliferous and alkaline deposition, which likewise permeates the dried mud underneath. So strongly saline are the waters of the lake, and so rapid the evaporation, as I found on trial, that one floats in spite of himself, and the under surfaces of the wooden steps leading into the water at the bathing-places are hung with short stalactites of salt from the evaporation of the drip of the emergent bathers.[1]

(*b*) Salt lakes of oceanic origin are comparatively few in number. In their case portions of the sea have been isolated by movements of the earth's crust, and these detached areas, exposed to evaporation, which is only partially compensated by inflowing rivers, have shrunk in level, and at the same time have sometimes grown much salter than the parent ocean. The Caspian Sea, 180,000 square miles in extent, and with a maximum depth of from 2000 to 3000 feet, is a magnificent example. The shells living in its waters are chiefly the same as those of the Black Sea. Banks of them may be traced

[1] Much information regarding the Great Basin and its lakes is to be found in vol. iii. of Wheeler's *Survey*, and in vols. i. and iv. of the *Survey of the 40th Parallel*.

between the two seas, with salt lakes, marshes, and other evidences to prove that the Caspian was once joined to the Black Sea, and had thus communication with the main ocean. In this case also there are proofs of considerable changes of water level. At present the surface of the Caspian is eighty-five and a half feet below that of the Black Sea. The Sea of Aral, also a salt basin, and once probably united with the Caspian, now rests at a level of 242·7 feet above that sheet of water. The steppes of South-eastern Russia are a vast depression with numerous salt lakes and abundant saline and alkaline deposits. It has been supposed that this depression continued far to the north, and that a great firth, running up between Europe and Asia, stretched completely across what are now the steppes and plains of the Tundras till it merged into the Arctic Sea. Seals of a species (*Phoca caspica*) which may be only a variety of the common northern form (*Ph. fœtida*) abound in the Caspian, which is the scene of one of the chief seal-fisheries of the world.[1] On the west side of the Ural chain, even at present, by means of canals connecting the rivers Volga and Dwina, vessels can pass from the Caspian into the White Sea.[2]

The cause of the isolation of the Caspian and the other saline basins of that region, is to be sought in underground movements which, according to Helmersen, are still in progress, but partly, and, in the case of the smaller basins, probably chiefly, in a general diminution of the water supply all over Central Asia and the neighbouring regions. The rivers that flow from the north towards Lake Balkash, and that once doubtless emptied into it, now lose themselves in the wastes and are evaporated before reaching that sheet of water, which is fed only from the mountains to the south. The channels of the Amur Darya, Sir Darya, and other streams bear witness also to the same general desiccation.[3] The change, however, must be extremely gradual. At present the amount of water supplied by rivers to the Caspian appears just to balance that removed by evaporation, though there are slight yearly or seasonal fluctuations.

Owing to the enormous volume of fresh water poured into it by these rivers, the Caspian is not as a whole so salt as the main ocean, and still less so than the Mediterranean. Nevertheless the inevitable result of evaporation is there manifested. Along the shallow pools which border this sea a constant deposition of salt is taking place, forming sometimes a pan or layer of rose-coloured crystals on the bottom, or gradually getting dry, and covered with drift sand. This concentration of the water is particularly marked in the great offshoot

[1] Another variety or species of seal inhabits Lake Baikal. For an account of the structures and distribution of seals see an interesting monograph by J. A. Allen in *Miscellaneous Publications of U.S. Geological and Geographical Survey of the Territories*. Washington, 1880.

[2] Count von Helmersen, however, has recently stated his belief that for this extreme northern prolongation of the Aralo-Caspian Sea there is no evidence. The shells, on the presence of which over the Tundras the opinion was chiefly based, are, according to him, all freshwater species, and there are no marine shells of living species to be met with in the plains at the foot of the Ural Mountains.

[3] *Bull. Acad. Imp. St. Petersbourg*, xxv. p. 535 (1879).

called the Karaboghaz, which is connected with the middle basin of the Caspian by a channel 150 yards wide and 5 feet deep. Through this narrow mouth there flows from the main sea a constant current, which Von Baer estimated to carry daily into the Karaboghaz 350,000 tons of salt. An appreciable increase of the saltness of that gulf has been noticed: seals, which once frequented it, have forsaken its barren shores. Layers of salt are gathering on the mud at the bottom, where they have formed a salt-bed of unknown extent, and the sounding-line, when scarcely out of the water, is covered with saline crystals.[1]

The following table shows the proportion of the saline materials in the waters of some salt lakes:

Constituent (except where otherwise stated).	Caspian Sea. Near mouth of R. Ural (Göbel).	Caspian Sea. At Baku (Abich).	Indertsch Lake (Göbel).	Great Salt Lake, Utah. (O. D. Allen.)	Elton Lake, Kirghis Steppe. (H. Rose.)	Dead Sea.
Chloride of Sodium	0·3673	8·5267	23·928	11·8628	3·83	3·6372
" Magnesium	0·0632	0·3039	1·736	1·4908	19·75	15·9774
" Calcium	0·0013 ($MgCO_3$)	..	..	..	..	4·7197
" Potassium	0·0076	trace	0·101	0·0862 (excess Chlorine)	0·23	0·8379
Bromide of Magnesium	trace.	..	0·005	..	..	0·8157
Sulphate of Calcium	0·0490	1·0742	0·042	0·0858	..	0·0889
" Potassium	0·0171 ($CaCO_3$)	0·0554 ($CaCO_3$)	..	0·5363	..	..
" Magnesium	0·1237	3·2493	0·346	0·9321 ($NaSO_4$)	5·32	..
Water	99·3806	86·7905	73·842	85·0060	70·87	73·9232
	100·0000	100·0000	100·000	100·000	100·000	100·0000

Deposits in Salt and Bitter Lakes.—The study of the precipitations which take place on the floors of modern salt lakes is important in throwing light upon the history of a number of chemically formed rocks. The salts in these waters accumulate until their point of saturation is reached, or until by chemical reaction they are thrown down. The least soluble are naturally the first to appear, the water becoming progressively more and more saline till it reaches a condition like that of the mother liquor of a salt work. Gypsum begins to be thrown down from sea-water when 37 per cent. of water has been evaporated, but 93 per cent. of water must be driven off before chloride of sodium can begin to be deposited. Hence the concentration and evaporation of the water of a salt lake having a composition like that of the sea would give rise first to a layer or sole of gypsum followed by one of rock-salt. This has been found to be the normal order among the various saliferous formations in the earth's crust. But gypsum may be precipitated without rock-salt, either because the water was diluted before the point of saturation for rock-salt was reached,

[1] Von Baer, *op. cit.* (1855-6). See also Carpenter, *Journ. Roy. Geog. Soc.* xviii. No. 4. For the composition of the water of salt and bitter lakes, see the analyses collected by Roth in his "Chemische Geologie," i. p. 463, *et seq.*

or because the salt, if deposited, has been subsequently dissolved and removed. In every case where an alternation of layers of gypsum and rock-salt occurs, there must have been repeated renewals of the water supply, each gypsum zone marking the commencement of a new series of precipitates.

But the composition of many existing saline lakes is strikingly unlike that of the sea in the proportions of the different constituents. Some of them contain carbonate of sodium; in others the chloride of magnesium is enormously in excess of the less soluble chloride of sodium. These variations modify the effects of the evaporation of additional supplies of water now poured into the lakes. The presence of the sodium carbonate causes the decomposition of lime salts and the consequent precipitation of calcium carbonate accompanied with a slight admixture of magnesium carbonate, while by further addition of the sodium carbonate a hydrated magnesium carbonate may be eventually precipitated. Hunt has shown that solutions of bicarbonate of lime decompose sulphate of magnesia with the consequent precipitation of gypsum, and eventually also of hydrated carbonate of magnesia, which, mingling with carbonate of lime, may give rise to dolomite.[1] By such processes the marls or clays deposited on the floors of inland seas and salt lakes may conceivably be impregnated and interstratified with gypseous and dolomitic matter, though in the Trias and other ancient formations which have been formed in enclosed saline waters, the magnesian chloride has probably been the chief agent in the production of dolomite (*ante* p. 305).

The Dead Sea, Elton Lake, and other very salt waters of the Aralo-Caspian depression are interesting examples of salt lakes far advanced in the process of concentration. The great excess of the magnesium chloride shows, as Bischof pointed out, that the waters of these basins are a kind of mother liquor, from which most of the sodium chloride has already been deposited. The greater the proportion of the magnesium chloride the less sodium chloride can be held in solution. Hence as soon as the waters of the Jordan and other streams enter the Dead Sea, their proportion of sodium chloride (which in the Jordan water amounts to from ·0525 to ·0603 per cent.) is at once precipitated. With it there goes down gypsum in crystals, also the carbonate of lime which, though present in the tributary streams, is not found in the waters of the Dead Sea. In spring the rains bring large quantities of muddy water into this sea. Owing to dilution and diminished evaporation, a check must be given to the deposition of common salt, and a layer of mud is formed over the bottom. As the summer advances, and the supply of water and mud decreases, while evaporation increases, the deposition of salt and gypsum again proceeds.[2] As the level of the Dead Sea is liable to variations, parts of the bottom are from time to time exposed, and show a surface of bluish gray clay or marl full

[1] Sterry Hunt, in "Geology of Canada" (1863), p. 575.
[2] Bischof, "Chem. Geol." i. p. 397. Roth, "Chem. Geol." i. p. 476.

of crystals of common salt and gypsum. Beds of similar saliferous and gypsiferous clays with bands of gypsum rise along the slopes for some height above the present surface of the water, and mark the deposits left when the Dead Sea covered a larger area than it now does. Save occasional impressions of drifted terrestrial plants, these strata contain no organic remains.[1] Interesting details regarding saliferous deposits of recent origin on the site of the Bitter Lakes were obtained during the construction of the Suez Canal. Beds of salt interleaved with laminæ of clay and gypsum crystals were found to form a deposit upwards of 30 feet thick, extending along 21 miles in length by about 8 miles in breadth. No fewer than 42 layers of salt, from 3 to 18 centimetres thick, could be counted in a depth of 2·46 metres. A deposit of earthy gypsum and clay was ascertained to have a thickness of 367 feet (112 metres), and another bed of nearly pure crumbling gypsum to be about 230 feet (70 metres) deep.[2]

The desiccated floors of the great saline lakes of Utah and Nevada have revealed some interesting facts in the history of saliferous deposits. The ancient terraces marking former levels of these lakes are cemented by tufa, which appears to have been abundantly formed along the shores where the waters of the brooks mingled with that of the lake and immediately parted with their lime. Even at present oolitic grains of carbonate of lime are to be found in course of formation along the margin of Great Salt Lake, though carbonate of lime has not been detected in the water of the lake, being at once precipitated in the saline solution. The site of the ancient salt lake which has been termed Lake Lahontan, displays areas several square miles in extent covered with deposits of calcareous tufa twenty to sixty and even one hundred and fifty feet thick. This tufa, however, presents a remarkable peculiarity. It is sometimes almost wholly composed of what have been determined to be calcareous pseudomorphs after gaylussite (a mineral composed of carbonates of calcium and sodium with water)—the sodium of the mineral having been replaced by calcium. When this tufa was originally formed, the waters of the vast lake must have been bitter, like those of the little soda lakes which now lie on its site—a dense solution in which carbonate of soda predominated. On the margin of one of the present Soda Lakes crystals of gaylussite now form in the drier seasons of the year. Yet no trace of carbonate of lime has been detected in the water. The carbonate of lime in the crystals must be derived from water, which on entering the saline lakes is at once deprived of its lime.[3]

§ 5. Terrestrial Ice.

Fresh water, under ordinary circumstances, when it reaches a temperature of 32° Fahr. passes into the solid state by crystallizing

[1] Lartet, *Bull. Soc. Géol.* (2nd sér.), xxii. p. 450, *et seq.*
[2] Lesseps, *Ann. Chim. et Phys.* (5), iii. p. 139. Bader, *Verhandl. K. K. Reichsanst.* 1869, p. 288.
[3] King, *Exploration of the 40th Parallel*, i. p. 510.

into ice. In this condition it performs a series of important geological operations before being again melted and relegated to the general mass of liquid terrestrial waters. Five conditions under which ice occurs on the land deserve notice, viz., frost, frozen rivers and lakes, hail, snow, and glaciers.

Frost.—Water in freezing expands. If it be confined in such a way that expansion is impossible, it remains liquid even at temperatures far below the freezing point; but the instant that the pressure is removed this chilled water becomes solid ice. There is a constant effort on the part of the water to expand and become solid, very considerable pressure being needed to counterbalance this expansive power, which increases as the temperature sinks. At 30° Fahr. the pressure must amount to 146 atmospheres, or the weight of a column of ice a mile high, or 138 tons on the square foot. Consequently when the water freezes at a lower temperature its pressure on the walls of its enclosing cavity must exceed 138 tons on the square foot. Bombshells and cannon filled with water and hermetically sealed have been burst in strong frosts by the expansion of the freezing water within them. In nature the enormous pressures which can be obtained artificially occur rarely or not at all, because the spaces into which water penetrates can hardly ever be so securely closed as to permit the water to be cooled down considerably below 32° Fahr. before freezing. But ice forming at even two or three degrees below the freezing point exerts an enormous disruptive force.

Soils and rocks being all porous, and usually containing a good deal of moisture, have their particles pushed asunder by the freezing of this interstitial water. Stones, stumps of trees or other objects imbedded in the ground are squeezed out of it. When a thaw comes, the soil seems as if it had been ground down in a mortar. Water freezing in the innumerable joints and fissures of rocks exerts great pressure upon the walls between which it lies, pushing them asunder as if a wedge were driven between them. When this ice melts, the separated masses do not return to their original position. Their centre of gravity in successive winters becomes more and more displaced, until the sundered masses fall apart. In mountainous districts, where the winters are severe, and in high latitudes, much waste is thus produced on exposed cliffs and loose blocks of rock. Some measure of its magnitude may be seen in the heaps of angular rubbish which in these regions so frequently lie at the foot of crags and steep slopes. At Spitzbergen and on the coast of Greenland the observed amount of destruction caused by frost is enormous. The short warm summer, melting the snow, fills the pores and joints of the rocks with water, which when it freezes splits off large blocks, launching them to the base of the declivities, where they are further broken up by the same cause.

Frozen Rivers and Lakes.—In countries such as Canada the lakes and rivers are frozen over in winter with a cake of ice $1\frac{1}{2}$ to $2\frac{1}{2}$

feet thick. A vast amount of anchor-ice is likewise formed on the bottoms of the rivers and rises to the surface. In several ways geological changes are thus effected. Mud, gravel, and boulders, encased in the anchor-ice or pushed along by it on the bottom, are moved from their position. This ice, formed in considerable quantity in the rapids of the Canadian rivers, is carried down stream and accumulates against the bars and banks or is pushed over upon the surface of the upper ice. By its accumulation a temporary barrier is formed, the bursting of which causes destructive floods. When the ice breaks up in early summer, cakes of it which have formed along shore and have enclosed beach-pebbles and boulders, float off so as either to drop these in deeper water or to strand them on some other part of the shore. This kind of transport takes place on a great scale on the St. Lawrence. The islets of boulder clay and solid rock are fringed with blocks which have been stranded by ice and which are ready to be again enclosed, and floated off further down stream. Should a gale arise during the breaking up of the frost, vast piles of ice, with mingled gravel and boulders, may be driven ashore and pushed up the beach; even blocks of stones of considerable size, are sometimes forced to a height of several yards, tearing up the soil on their way, and helping to form a bank above the water level. In the same river great destruction of banks has been caused by rafts of ice, and particularly of anchor-ice. Crab Island, for example, which was about an acre and a half in extent at the beginning of this century, has entirely disappeared, its place being indicated merely by a strong ripple of the water, which is every year getting deeper over the site.[1] Other islands have also been destroyed. Great damage is frequently done to quays and bridges in the same region by masses of river-ice driven against them on the arrival of spring. Reference has already been made to the increased power of transport and erosion acquired by rivers liable to be frozen over, and especially when their ice is broken up in the higher parts of their courses, before it gives way in the lower (p. 368).

Hail, the formation of which is not yet well understood, falls chiefly in summer and during thunderstorms. When the pellets of ice are frozen together so as to reach the ground in lumps as large as a pigeon's egg, or larger, great damage is often done to cattle, flying birds, and vegetation. Trees have their leaves and fruit torn off, and farm crops are beaten down.

Snow.—In those parts of the earth's surface where, either from geographical position or from elevation into the upper cold regions of the atmosphere, the mean annual temperature is below the freezing point, the condensed moisture falls chiefly as snow, and remains in great measure unmelted throughout the year. A line termed the *snow-line* can be traced, below which the snow disappears in summer, but above which it continues to cover the whole or great part of the surface. The snow-line comes down to the sea within the

[1] Bleasdell, *Q. J. Geol. Soc.* xxvi. p. 669; xxviii. p. 292.

polar circles. Between these limits it rises gradually in level till it reaches its highest elevation in tropical latitudes. South of lat. 78° N. it begins to retire from the sea-level, so that on the coast of northern Scandinavia it is already nearly 3000 feet above the sea. None of the British mountains quite reach it. In the Alps it stands at 8500 feet, on the Andes at 18,000 feet, and on the northern slopes of the Himalayas at 19,000 feet.

Snow exhibits two different kinds of geological behaviour, (1) conservative, and (2) destructive. (1) Lying stationary and unmelted it exercises a protective influence on the face of the land, shielding rocks, soils, and vegetation from the effects of frost. On low grounds this is doubtless its chief function. (2) When snow falls in a partially melted state it is apt to accumulate on branches and leaves, until by its weight it breaks them off, or even bears down entire trees. Great destruction is thus caused in dense forests. Snow which falls thickly on steep mountain slopes is frequently during spring and summer detached in large sheets. These rush down the declivities as *avalanches*, and sweep away trees, soil, crops, and houses. Another indirect effect of snow is seen in the sudden rise of rivers when warm weather rapidly melts the mountain snows. Many summer freshets are thus caused in Switzerland. It is to the melting of the snows, rather than to rain, that rivers descending from snowy mountains owe their periodical floods. Hence such rivers attain their greatest volume in summer. A curious destructive action of snow has been observed on the sides of the Rocky Mountains, where the drifting of snow crystals by the wind in some of the passes has damaged and even killed the pine trees, wearing away the foliage, cutting off the bark and even sawing into the wood for several inches.[1]

Glaciers[2] are rivers of ice formed by the slow movement and compression of the snow which by gravitation creeps downward into valleys descending from snow-fields. The snow in the higher regions is loose and granular. As it moves downward it becomes firmer, passing into the condition of *nevé* or *firn* (p. 111). Gradually as the separate granules are pressed together and the air is squeezed out, the mass assumes the character of blue compact crystalline ice. From a geological point of view a glacier may be regarded as the drainage of the snowfall above the snow-line, as a river is the drainage of the rainfall. A glacier, like a river, is always in motion, though so slowly that it seems to be solid and stationary. The motion also, like that of a river, and for the same reason, is unequal in the different parts, the centre moving faster than the sides and bottom. This important fact was first ascertained through accurate measure-

[1] Clarence King, *Exploration of 40th Parallel*, i. p. 527.

[2] On glaciers and their geological work, see De Saussure, "Voyages dans les Alpes," § 535: Agassiz, "Études sur les glaciers," 1840; Rendu, "Théorie des glaciers de la Savoie," *Mem. Acad. Savoie*, x., translated into English 1875; J. D. Forbes, "Travels in the Alps," 1843; "Norway and its Glaciers," 1853; "Occasional Papers on Glaciers," 1859; Tyndall, "Glaciers of the Alps," 1857; Mousson, "Gletscher der Jetztzeit," 1854.

ment by J. D. Forbes, who found that in the Mer de Glace of Chamouni, the mean daily rate of motion in the summer and autumn was from 20 to 27 inches in the centre, and from 13 to 19½ near the side. Helland has observed that on the west coast of Greenland the glacier of Jacobshavn has a remarkably rapid motion, its rate for twenty-four hours ranging from 14·70 metres (48·2 feet) to 19·77 metres (64·8 feet). The consequence of this differential motion is seen in the internal banded structure of a glacier, in the downward curvature of the transverse fissures (crevasses), and in the arrangement of the lines of rubbish thrown down at the termination, which often present a horse-shoe shape, corresponding to that of the end of the ice by which they were discharged.[1]

Some features of geological importance in the behaviour of the ice as it descends its valley deserve mention here. When a glacier has to travel over a very uneven floor, some portions may get embayed, while overlying parts slide over them. A massive ice-sheet may thus have many local eddies in its lower portions, the ice there even travelling for various distances, according to the nature of the ground, obliquely to the general flow of the main mass. In descending by a steep slope to a more level part of its course, a glacier becomes a mass of fissured ice in great confusion. It descends by a slowly creeping ice-fall, where a river would shoot over in a rushing waterfall. A little below the fall the fractured ice, with all its chaos of pinnacles, bastions, and chasms, is pressed together again into a solid mass as before (Fig. 135).

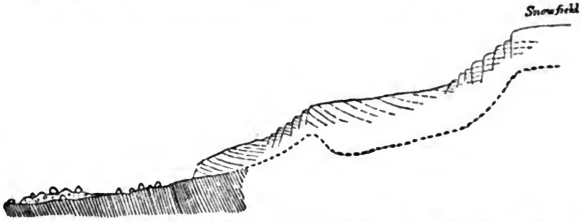

Fig. 135.—Section of Glacier with Ice-falls, Fondalen, Holands Fjord, Arctic Norway.

The body of the glacier throughout its length is traversed by a set of fissures called *crevasses*, which, though at first as close-fitting as cracks in a sheet of glass, widen by degrees as the glacier moves on, till they form wide yawning chasms, reaching, it may be, to the bottom of the ice, and travelling down with the glacier, but apt to

[1] The cause of glacier motion has been a much-vexed question in physics. See besides the works cited on the foregoing page, J. Thomson, *Proc. Roy. Soc.* 1856–7; Mosely, *op. cit.* 1869; Croll, "Climate and Time," 1875; Hopkins, *Phil. Mag.* 1845; *Phil. Trans.* 1862; Helmholtz, *Heidelberg Verhandl. Nat. Med.* 1865, p. 194; *Phil. Mag.* 1866, p. 22; Pfaff, *Akad. Bayer.* 1876.

FIG. 136.—MONT BLANC AND ITS SURROUNDING MOUNTAINS AND GLACIERS, AS SEEN FROM THE BRÉVENT, A MOUNTAIN OPPOSITE TO CHAMOUNI (*B.*).

be effaced by the pressing of their walls together again as the glacier winds down its valley. The glacier continues to descend until it reaches that point where the supply of ice is just equalled by the liquefaction. There it ends, its place down the rest of the valley being taken by the tumultuous river of muddy water which escapes from under the melting extremity of the ice. A prolonged augmentation of the snowfall will send the foot of the glacier further down the valley; a diminution of the snowfall with a general rise of temperature will cause it to retreat farther up. Considerable variations in the thickness and length of glaciers have been observed within the last two or three generations. Thus the glacier of La Brenva, on the Italian side of Mont Blanc, shrank to such an extent in the twenty-four years succeeding 1818, that its surface at one place was found to have subsided no less than 300 feet.[1]

In a mountainous region, such as the Alps, or a table-land like Scandinavia, where a considerable mass of ground lies above the snow-line, three varieties of glaciers may be observed.

(1) Glaciers of the first order come down well below the snow, and extend into the valleys. In high latitudes they reach the sea. In the Alps such glaciers may be 20 or 30 miles long, by a mile or more wide, and 800 feet or more deep. The spiry peaks and sharp crests of these mountains everywhere rise through the snow which they thus isolate into distinct basins, whence glaciers proceed. The total number of glaciers among the Alps has been estimated at 2000, covering a total area of 1838·8 square kilometres. A striking contrast to the character of Alpine glacier scenery is presented by the great snow-fields of Arctic Norway. These accumulate on broad table-lands, from which they send glaciers down into the valleys (Figs. 137 and 139).

Fig. 137.—View of the two Glaciers of Fondalen, Holands Fjord, Arctic Norway.

(2) Glaciers of the second order hardly creep beyond the high recesses wherein they are formed, and do not therefore reach as far as

[1] J. D. Forbes, *Travels in the Alps*, p. 205.

the nearest valley. Many beautiful examples of this type may be seen along the steep declivities which intervene between the snow-covered plateau of Arctic Norway and the sea.

(3) Re-cemented Glaciers (*Glaciers remaniés*). These consist of fragments which fall from an ice-cliff crowning precipices of rock, and are re-frozen at the bottom into a solid mass, creeping downward as a glacier usually of the second order. Probably the best illustrations in Europe are furnished by the Nus Fjord, and other parts of the north of Norway. In some cases a cliff of firn resting on blue ice appears at the top of the precipice,—the edge of the great "sneefond," or snow-field,—while several hundred feet below, in the corrie or cwm at the bottom, lies the re-cemented glacier, white at its upper edge, but acquiring somewhat of the characteristic blue gleam of compact ice as it moves towards its lower margin. A beautiful example of this kind was visited by me at the head of the Jokuls Fjord in Arctic Norway in 1865. When making the sketch, from which Fig. 138 is taken, I observed that the ice from the edge of the

FIG. 138.—VIEW OF RE-CEMENTED GLACIER, JOKULS FJORD, ARCTIC NORWAY.

snow-field above slipped off in occasional avalanches, which sent a roar as of thunder down the valley, while from the shattered ice, as it rushed down the precipices, clouds of white snow-dust rose into the air. The débris thus launched into the defile beneath accumulates there by mutual pressure into a tolerably solid mass, which moves downward as a glacier and actually reaches the sea-level—the only example, so far as I am aware, of a glacier on the continent of Europe which attains so low an altitude. As it descends it is crevassed and when it comes to the edge of the fjord, slices from time to time slip off into the water where they form fleets of miniature icebergs with which the surface of the fjord (*f* in Fig. 139) is covered.

But it is in high Arctic, and still more in Antarctic, latitudes that land-ice, formed from the drainage of a great snow-field, attains its greatest dimensions. The land in these regions is

buried under an ice-cap, which ranges in thickness up to a depth (in the South Polar circle) of 10,000 feet (2 miles) or even more. Greenland lies under such a pall of snow that all its inequalities, save the mere steep mountain crests and peaks near the coast, are

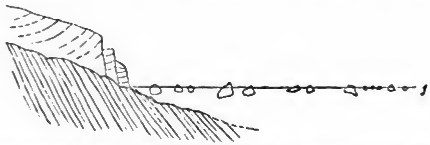

Fig. 139.—Section showing the Production of Icebergs at the Foot of the Jokuls Fjord Glacier.

concealed. The snow creeping down the slopes, and mounting over the minor hills, passes beneath by pressure into compact ice. From the main valleys great glaciers like vast tongues of ice, 2000 or 3000 feet thick, and sometimes 50 miles or more in breadth, push out to sea, where they break off in huge fragments, which float away as icebergs. As far back as 1777, Captain Cook gave interesting descriptions of the glaciers of South Georgia (Lat. 54° S.), which reach the sea in a line of cliffs (Fig. 140).

Fig. 140.—View of Glacier in Possession Bay, South Georgia.

Work done by Glaciers.—Glaciers have two important geological tasks to perform—(1) to carry the débris of the mountains down to lower levels; and (2) to erode their beds.

(*a*) *Transport.*—This takes place chiefly on the surface of the ice. Descending its valley, the glacier receives and bears along on its margin

the earth, stones, and rubbish which, loosened by frost, or washed down by rain and rills, slip from the cliffs and slopes. In this part of its work the glacier resembles a river which carries down branches and leaves from the woods on its banks. Most of the detritus rests on the surface of the ice. It includes huge masses of rock, sometimes as big as a large cottage, all which, though seemingly at rest, are slowly travelling down the valley with the ice, and liable at any moment to slip into the crevasses which may open below them. When they thus disappear they may descend to the bottom of the ice,

FIG. 141.—VIEW OF THE UPPER PART OF THE ZERMATT GLACIER (AGASSIZ).
Showing longitudinal lines of moraines and transverse crevasses. The moraines on the left descend from Monte Rosa and the Gornerhorn, those on the right from the Little Cervin and Furke-flue.

and move with it along the rocky floor, which is no doubt the fate of a large proportion of the smaller stones and sand. But the large stones seem sometimes at least to be cast up again by the ice to the surface of the glacier at a lower part of its course. Whether, therefore, on the ice, in the ice, or under the ice, a vast quantity of detritus is continually travelling with the glacier down towards the plains. The rubbish lying on the surface is called *moraine* stuff. Naturally it accumulates on either side of the glacier, where it forms the so-called *lateral moraines.* When two glaciers unite, their two adjacent lateral

moraines are brought together, and travel thereafter down the centre of the glacier as a *medial moraine* (Figs. 141, 142, and 143).

Fig. 142.—View of the medial Moraines and Glacier Tables of the Aar Glacier (Agassiz).

In Fig. 143 the left lateral moraine (3) of glacier B unites with the right lateral moraine (2) of A to form the medial moraine *b*, while the other moraines (1, 4) continue their course and become respectively the right and left lateral moraines (*a c*) of the united

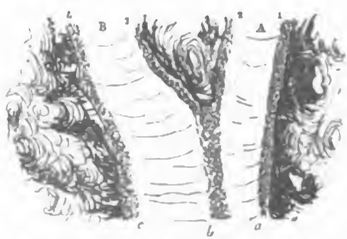

Fig. 143.—Map of the Union of two Glaciers, showing Junction of two Lateral into one Medial Moraine.

glacier. A glacier, formed by the union of many tributaries in its upper parts, may have numerous medial lines of moraine (Fig. 141),

so many indeed as sometimes to be covered with débris to the complete concealment of the ice. At such parts the glacier appears to be a bare field or earthy plain rather than a solid mass of clear ice of which only the surface is dirty with rubbish. At the end of the glacier the pile of loose materials is tumbled upon the valley in what is called the *terminal moraine.*

In such comparatively small and narrow ice-sheets as the present glaciers of Switzerland, the rock bottom on which the ice moves is usually, as far as it can be examined, swept clean by the trickle or rush of water over it from the melting ice. But when the ice does not flow in a mere big drain (which, after all, the largest Alpine valley really is), but overspreads a wide area of uneven ground, there cannot fail to be a great accumulation of rubbish here and there underneath it. The sheet of ice that once filled the broad central plain of Switzerland between the Alps and the Jura certainly pushed a vast deal of mud, sand, and stones over the floor of the valley. This material is known to Swiss geologists as the *moraine profonde* or *Grundmoräne*[1] (=boulder clay, till or bottom-moraine).

When from any cause a glacier diminishes in size, it may drop its blocks upon the sides of its valley, and leave them there sometimes in the most threatening positions. Such stranded stones are known as *perched blocks* (Fig. 144). Those of each valley belong to

FIG. 144.—VIEW OF AN ALPINE VALLEY WITH PERCHED BLOCKS HIGH ON ITS FLANKS (*B.*).

the rocks of that valley; and if there be any difference between the rocks on the two sides, the perched blocks carried far down from their sources still point to that difference, for they remain on their own original side. But during a former great extension of the glaciers of the northern hemisphere, blocks of rock have been carried out of

[1] In 1869 I examined a characteristic section of it near Solothurn, full of scratched stones, and lying on the striated pavement of rock to be immediately described as further characteristic of ice-action.

their native valleys, across plains, valleys, and even considerable ranges of hills. Such "erratics" (Findlinge) not only abound in the Swiss valleys, but cross the great plain of Switzerland, and appear in numbers high upon the flanks of the Jura. Since the latter mountains consist chiefly of limestone, and the blocks are of various crystalline rocks belonging to the higher parts of the Alps, the proof of transport is irrefragable. Thousands of them form a great belt of boulders extending for miles at an average height of 800 feet above the Lake of Neufchâtel (Fig. 145). These consist of the protigine granite of

Fig. 145.—Pierre à Bot—a Granitic block from the Mont Blanc Range, stranded above Neufchâtel (J. D. Forbes).

the Mont Blanc group of mountains, and must have travelled at least 60 or 70 miles. One of the most noted of them, the Pierre à Bot (toad-stone), which lies about two miles west of Neufchâtel, measures 50 (French) feet in length by 20 in width, and 40 in height. It is estimated to contain 40,000 cubic feet, and to weigh about 3000 tons.[1] The celebrated "blocks of Monthey" consist of huge masses of granite, disposed in a belt, which extends for miles along the mountain slopes on the left bank of the Rhone, near its union with the Lake of Geneva. On the southern side of the Alps similar evidence of the transport of blocks from the central mountains is to be found. On the flanks of the limestone heights on the further side of the Lake of Como, blocks of granite, gneiss, and other crystalline rocks lie scattered about in hundreds (Fig. 146).

Fig. 146.—Angular erratic Block on the north side of the Alpi di Pravolta Lake of Como (B.).

Before the numerous facts had been collected and understood which prove a former great augmentation in the size of the Alpine

[1] Forbes, "Travels in the Alps," p. 49.

glaciers, it was believed by many geologists that the erratics stranded along the flanks of the Jura Mountains had been transported on floating ice, and that Central Europe was then in great part submerged beneath an icy sea. It is now universally admitted, however, that the transport has been entirely the work of glaciers. Instead of being confined as at present to the higher parts of their valleys, the glaciers extended down into the plains. As already stated, they filled the great depression between the Oberland and the Jura, and rising high upon the flanks of the latter chain, actually overrode

FIG. 147.—SECTION TO SHOW THE EXTENSION OF THE ALPINE GLACIERS (*a*) ACROSS THE PLAIN OF SWITZERLAND, AND THE TRANSPORT OF BLOCKS TO THE SIDES OF THE JURA (*m*) (*B.*).

some of its ridges. Similar evidence abounds in the hilly parts of Britain, as well as in other parts of Europe and America, no longer the abode of glaciers, that a great extension of snow and ice at a recent geological period prevailed in the northern hemisphere, as will be described in the account of the Glacial Period in Book VI. There is proof also that the glaciers of New Zealand were formerly much larger.

As De la Beche has well pointed out, the student must be on his guard, however, lest he be led to mistake for true erratics mere weathered blocks belonging to a rock that has disintegrated *in situ*. If, for example, he should encounter a block like that represented in Fig. 148, he would properly conclude that it had travelled because it did not belong to the rock on which it lay. But he would require to prove further that there was no rock in the immediate neighbourhood from which it could have fallen as the result of mere weathering. The granite (*c*) shown in Fig. 149, disintegrates at the summit, and the blocks into which it splits find their way by gravitation down the slope.[1]

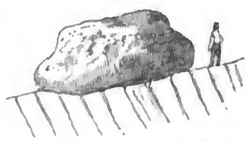

FIG. 148.—BLOCK OF GRANITE RESTING ON INCLINED STRATA (*B.*).

(*b*) *Erosion.*—The manner and the results of erosion in the channel of a glacier differ from those associated with other geological agents, and form therefore distinguishing features of ice-action. This erosion is effected not by the mere contact and pressure of the ice upon the rocks (though undoubtedly fragments of rock must now and then be detached from this cause), but by means of the fine sand, stones, and blocks of rock, that fall between the ice and the rocks on which it moves. The

[1] De la Beche, *Geological Observer*, p. 257.

detritus thus introduced is, for the most part, fresh and angular. Its trituration by the glacier reduces the size of the particles, but retains their angular character, so that, as Daubrée has pointed out, the sand that escapes from the end of a glacier appears in

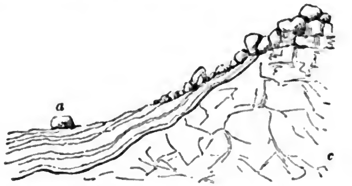

Fig. 149.—Granite (*c*) decomposing into Blocks (*a*) which gradually roll down upon the surrounding Stratified Rocks (*B*.).

the condition of sharp freshly-broken grains, and not as rounded water-worn particles.[1]

The surface of a glacier being often strewn with earth and stones, these materials are frequently precipitated into the crevasses, and may thus reach the rocky floor over which the ice is moving. They likewise fall into the narrow space which sometimes intervenes between the margin of a glacier and the side of the valley (*a* in Fig. 150). Held by the ice as it creeps along, they are pressed against the rocky sides and bottom of the valley so firmly and persistently as to descend into each little hollow and mount over each ridge, yet all the while moving along steadily in one dominant direction with the general movement of the glacier. Here and there the ice, with grains of sand and pieces of stone imbedded in its surface, can be caught in the very act of polishing and scouring the rocks. In Fig. 151 a view is given of the "angle" on the Mer de Glace, Chamouni, where blocks of granite are jammed between the mural edge of the ice and the precipice of rock along which it moves, and which is scored and polished in the direction of motion of the blocks. Under the slow, continuous, and enormous erosive power of the creeping ice, the most compact resisting rocks are ground down, smoothed, polished, and striated. The striæ vary from such fine lines as may be made by the smallest grains of quartz up to deep ruts and grooves. They sometimes cross each other, one set partially effacing an older one, and thus pointing to shiftings in the movement of the ice. On the retirement of the glacier, hummocky bosses of

Fig. 150.—Section of a Glacier in its Rocky Channel,

With a medial moraine at *d*, a lateral moraine partly on the ice and partly stranded on a sloping declivity (*b*), a mass of rocks fallen between the ice and the precipitous rocks at *a*, and a group of perched blocks at *c*. (J. D. Forbes.)

[1] "Géologie Expérim." p. 254.

rock having smooth undulating forms like dolphins' backs are conspicuous. These have received the name of *roches moutonnées.* The stones by which this scratching and polishing are effected suffer in exactly the same way. They are ground down and striated, and since they must move in the line of least resistance, or "end on,"

FIG. 151.—VIEW OF PART OF THE SIDE OF THE MER DE GLACE (J. D. FORBES).

their striæ run in a general sense lengthwise (Fig. 154). It will be seen, when we come to notice the traces of former glaciers, how important is the evidence given by these striated stones.

Besides its proper and characteristic rock-erosion, a glacier is aided in a singular way by the co-operation of running water. Among the Alps during day in summer much ice is melted and the water courses over the glaciers in brooks which, as they reach the crevasses, tumble down in rushing waterfalls, and are lost in the depths of the ice. Directed, however, by the form of the ice-passage against the rocky floor of the valley, the water descends at a particular spot, carrying with it the sand, mud, and stones which it may have swept away from the surface of the glacier. By means of these materials it erodes deep pot-holes (moulins) in the solid rock, in which the rounded detritus is left as the crevasse closes up or moves down the valley. On the ice-worn surface of Norway singular cavities

of this kind, known as "giants' kettles" (Fig. 153), exist in great numbers. There can be little doubt that they have had an origin

Fig. 152.—Ice-worn Surface of Rock, showing Polish, Striæ, and Groovings.

under the massive ice-cover which once spread over that peninsula. The Greenland ice-sheet is traversed in summer by powerful rivers which are swallowed up in the crevasses. Excavations of the same nature are no doubt also in progress there.[1]

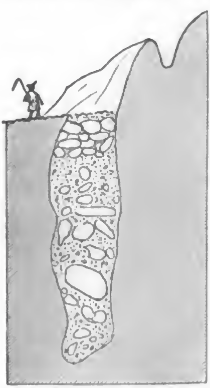

Fig. 153.—Section of "Giants' Kettles," near Christiania.

As rocks present great diversities of structure and hardness, and consequently vary much in the resistance they offer to denudation, they are necessarily worn down unequally. The softer, more easily eroded portions are scooped out by the grinding action of the ice, and basin-shaped or various irregular cavities are dug out below the level of the general surface. Similar effects may be produced by a local augmentation of the excavating power of a glacier, as where the ice is strangled in some narrow part of a valley, or where, from change in declivity, it is allowed to accumulate in greater mass as it moves more slowly onward. Such hollows, on the retirement of the ice, become receptacles for water, and form pools, tarns, or lakes,

[1] Brögger and Reusch, *Q. J. Geol. Soc.* xxx. 750.

unless, indeed, they chance to have been already filled up with glacial rubbish.

It is now some years since Professor A. C. Ramsay drew attention to this peculiar power of land-ice, and affirmed that the abundance of excavated rock-basins in Northern Europe and America was due to the fact that these regions had been extensively eroded by sheets of land-ice,[1] when the more northern parts of the two continents were in a condition like that of North Greenland at the present day. It is among the ice-fields of Greenland rather than among the valley-glaciers of isolated mountain groups that the operations which produced the widespread general glaciation of the period of the rock-basins find their nearest modern analogies.

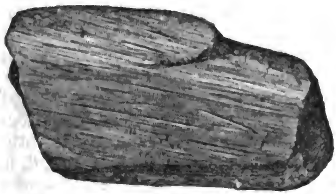

FIG. 154.—STRIATED STONE FROM BOULDER CLAY.

A single valley-glacier retires towards its parent snow-field as the climate ameliorates, leaving its *roches moutonnées*, moraine-mounds, and rock-basins, yet at times discharging its water-drainage in such a way as to sweep down the moraine-mounds, fill up the basins, bury the ice-worn hummocks of rock, and strew the valley with gravel, earth, sand, and big blocks of rock. Hence the actual floor of the glacier is apt to be obscured. But in the case of a vast sheet of land-ice covering continuously a wide region, there can be but little superficial débris. When such a mass of ice retires it must leave behind it an ice-worn surface of country more or less strewn with the detritus which accumulated under the ice and was pushed along by it. This infra-glacial débris forms the *Grundmoräne* (*moraine profonde*) or bottom moraine above referred to (p. 411). We know as yet very little regarding its formation in Greenland. Most of our knowledge regarding it is derived from a study of the till or boulder-clay in more southern latitudes, which is believed to represent the bottom moraine of an ancient ice-sheet. In countries where true boulder-clay occurs, numerous rock-basins are commonly to be met with among the uncovered portions of the rocks. These and other features of glaciated Europe and America will be more fully described in the account of the Glacial Period (Book VI.).[2]

[1] *Q. J. Geol. Soc.* xviii. (1862), p. 185. See also a paper by A. Helland (*op. cit.* xxxiii. p. 142), on the ice-fjords of North Greenland, and the formation of Fjords, Lakes, and Cirques.

[2] See the remarks already made (p. 338) on the possibility of the rotting out of

Hardly anything has yet been done in the way of actual measurement of the rate of erosion by different glaciers. An approximation to the truth might be obtained from the abundant fine sediment which, giving the characteristic milky turbidity to all streams that escape from the melting ends of glaciers, is an index of the amount of this erosion. The average quantity of sediment discharged from the melting end of a glacier during a year, having been estimated, it would be easy to determine its equivalent in the precise fraction of a foot of rock annually removed from the area drained by the glacier. From the end of the Aar glacier (which with its affluents is computed to have an area of 60 square kilometres, and is therefore by no means one of the largest in Switzerland) it has been estimated that there escape every day in the month of August 2 million cubic metres (440 million gallons) of water, containing 284,374 kilogrammes (280 tons) of sand. Mr. A. Helland has computed that from the Justedal glacier, Norway, one million kilogrammes of sediment are discharged in a July day, and that the total annual discharge from the ice-field, 830 square miles in area, amounts to 180 millions of kilogrammes, besides 13 million kilogrammes of mineral matter in solution. Taking the specific gravity of the suspended matter at 2·6, he finds that the basin of the glacier loses 69,000 cubic metres of solid rock every year, or a cubic mass measuring 41 metres on the side.[1] There is some difficulty, however, in determining what proportion of the sediment may have been washed in below the ice by streams issuing from springs and melted snows. Estimates of the work done by glaciers, so far as based upon the amount of sediment discharged by them, may consequently be rather over the truth.

§. 6. Oceanic Waters.

The area, depth, temperature, density, and composition of the sea having been already treated of (Book II.), we have now to consider its place among the dynamical agents in geology. In this relation it may be studied under two aspects: 1st, its movements, and 2nd, its geological work.

I. Movements.—(1.) *Tides.*—These oscillations of the mass of the oceanic waters caused by the attraction of the sun and moon require notice here only as regards their geological bearings. In a wide deep ocean the tidal elevation probably produces no perceptible geological change. It passes at a great speed; in the Atlantic its rate is 500 geographical miles an hour. But as this is merely the passing of an oscillation whereby the particles of water are gently

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basin-shaped receptacles in solid rock through the operations of superficial weathering —a process which may account for many rock-basins that have subsequently had their decomposed rock swept out of them by ice.

[1] *Aftryk ur Geol. Fören. Stockholm Förhandl.* 1874. No. 21. Band ii. No. 7.

raised up and let down again, there can hardly be any appreciable effect upon the deep ocean bottom. When, however, the tidal wave enters a narrow and shallow sea, it has to accommodate itself to a smaller channel, and encounters more and more the friction of the bottom. Hence, while its rate of motion is diminished, its height and force are increased. It is in shallow water and along the shores of the land that the tides acquire their main geological importance. They there show themselves in an alternate advance upon and retreat from the coast. Their upper limit has received the name of *high-water mark*, their lower that of *low-water mark*, the littoral space between being termed the *beach* (Fig. 155). If the coast is

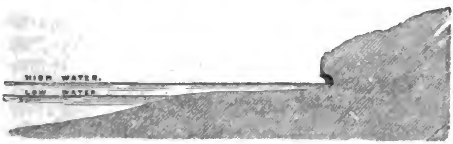


FIG. 155.—SECTION OF A BEACH DEFINED BY HIGH- AND LOW-WATER MARK.

precipitous, a beach can only occur in shelving bays and creeks, since elsewhere the tides will rise and fall against a face of rock, as they do on the piers of a port. On such rocky coasts the line of high water is sometimes admirably defined by the grey crust of barnacles adhering to the rocks. Where the beach is flat, and the rise and fall of the tide great, several hundred square miles of sand or mud may be laid bare in one bay at low-water.

The height of the tide varies from zero up to 60 or 70 feet. It is greatest where, from the form of the land, the tidal wave is cooped

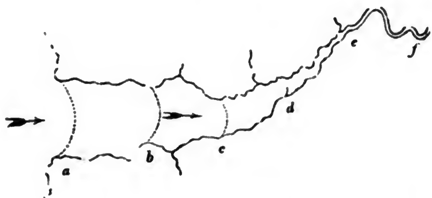


FIG. 156.—EFFECT OF CONVERGING SHORES UPON THE TIDAL WAVE.
The tide wave running up in the direction of the arrows rises successively higher at *a*, *b*, and *c* to *d*, after which it slackens and dies away at the upper limit of tides, *f*.

up within a narrow inlet or estuary. Under such circumstances the advancing tide sometimes gathers itself into one or more large waves, and rushes furiously up between the converging shores. This is the origin of the "bore" of the Severn, which rises to a height of 9 feet,

while the rise and fall of the tide there amounts to 40 feet. In like manner the tides which enter the Bay of Fundy, between Nova Scotia and New Brunswick, get more and more cooped up and higher as they ascend that strait, till they reach a height of 70 feet.

While the tidal swelling is increased in height by the shallowness and convergence of the shores, it gains at the same time force and rapidity. No longer a mere oscillation or pulsation of the great ocean, the tide acquires a true movement of translation, and gives rise to currents which rush past headlands and through narrows in powerful streams and eddies. The rocky and intricate navigation of the west of Scotland and Scandinavia furnishes many admirable illustrations of the rapidity of these tidal currents. The famous whirlpool of Corryvreckan, the lurking eddies in the Kyles of Skye, the breakers at the Bore of Duncansbay, and the tumultuous tideway, grimly named by the northern fishermen the Merry Men of Mey, in the Pentland Firth, bear witness to the strength of these sea rivers. At the last mentioned strait the current at its strongest runs at the rate of 10 miles an hour, which is fully three times the speed of most of our large rivers.

(2.) *Currents.*—Recent researches in ocean temperature have disclosed the remarkable fact that beneath the surface layer of water affected by the temperature of the latitude there lies a vast mass of cold water, the bottom temperature of every ocean in free communication with the poles being little above and sometimes actually below the freezing point of fresh water.[1] In the North Atlantic a temperature of 40° Fahr. is reached at an average depth of about 800 fathoms, all beneath that depth being progressively colder. In the equatorial parts of that ocean the same temperature comes to within 300 fathoms of the surface. In the South Atlantic, off Cape of Good Hope, the mass of cold water (below 40°) rises likewise to about 300 fathoms from the surface. This distribution of temperature proves that there must be a transference of cold polar water towards the equator, for in the first place the temperature of the great mass of the ocean is much lower than that which is normal to each latitude, and in the second place it is much lower than that of the superficial parts of the earth's crust underneath. On the other hand, the movement of water from the poles to the equator requires a return movement of compensation from the equator to the poles, and this must take place in the superficial strata of the ocean. Apart therefore from those rapid river-like streams which traverse the ocean, and to which the name of currents is given, there must be a general drift of warm surface water towards the poles. This is doubtless most markedly the case in the North Atlantic, where, besides the current of the Gulf Stream, there is a

[1] See in particular memoirs by Carpenter & Wyville Thomson, *Proc. Roy. Soc.* xvii. (1868), *Brit. Assoc.* xli. *et seq.*, *Proc. Roy. Geograph. Soc.* xv. Reports to the Admiralty of the *Challenger* Exploring Expedition. Wyville Thomson's "Depths of the Sea," 1873, and "Atlantic," 1877.

prevalent set of the surface waters towards the north-east. As the distribution of life over the globe is everywhere so dependent upon temperature, it becomes of the highest interest to know that a truly arctic submarine climate exists everywhere in the deeper parts of the sea. With such uniformity of temperature we may anticipate that the abysmal fauna will be found to possess a corresponding sameness of character, and that arctic types may be met with even on the ocean-bed at the equator.

But besides this general drift or set, a leading part in oceanic circulation is taken by the more defined streams termed currents. The tidal wave only becomes one of translation as it passes into shallow water, and is thus of only local consequence. But a vast body of water, known as the Equatorial Current, moves in a general westerly direction round the globe. Owing to the way in which the continents cross its path, this current is subject to considerable deflections. Thus that portion which crosses the Atlantic from the African side strikes against the mass of South America, and divides, one portion turning towards the south and skirting the shores of Brazil; the other bending north-westward into the Gulf of Mexico, and issuing thence as the well-known Gulf Stream. This equatorial water is comparatively warm and light. At the same time the heavier and colder polar water moves towards the equator, sometimes in surface currents like those which skirt the eastern and western shores of Greenland, but more generally as a cold under-current which creeps over the floor of the ocean even as far as the equator.

Much discussion has arisen in recent years as to the cause of oceanic circulation. Two rival theories have been given. According to one of these the circulation entirely arises from that of the air. The trade-winds blowing from either side of the equator drive the water before them until the north-east and south-east currents unite in equatorial latitudes into one broad westerly-flowing current. Owing to the form of the land, portions of this main current are deflected into temperate latitudes, and, as a consequence, portions of the polar water require to move towards the equator to restore the equilibrium. According to the other view the currents arise from differences of temperature (and according to some of salinity also); the warm and light equatorial water is believed to stand at a higher level than the colder and heavier polar water; the former, therefore, flows down as it were polewards, while the latter moves as a bottom inflow towards the equator; the cold bottom water under the tropics is constantly ascending to the surface, whence, after being heated, it drifts away towards the pole, and on being cooled down there, descends and begins another journey to the equator. There can be no doubt that the winds are directly the cause of such currents as the Gulf Stream, and therefore, indirectly, of return cold currents from the polar regions. It seems hardly less certain that, to some extent at least, differences of

temperature, and therefore of density, must occasion movements in the mass of the oceanic waters.[1]

Apart from disputed questions in physics, the main facts for the geological reader to grasp are—that a system of circulation exists in the ocean; that warm currents move round the equatorial regions, and are turned now to the one side, now to the other, by the form of the continents along and round which they sweep; that cold currents set in from poles to equator; and that, apart from actual currents, there is an extremely slow "creep" of the polar water under the warmer upper layers to the equator.

(3.) *Waves and Ground-Swell.*—A gentle breeze curls into ripples the surface of water over which it blows. A strong gale or furious storm raises the surface into waves. The agitation of the water in a storm is prolonged to a great distance beyond the area of the original disturbance, and then takes the form of the long heaving undulations termed ground-swell. Waves which break upon the land are called breakers, and the same name is applied to the ground-swell as it bursts into foam and spray upon the rocks. The concussion of earthquakes sometimes gives rise to very disastrous ocean waves (p. 272).

The height and force of waves depend upon the breadth and depth of sea over which the wind has driven them, and the form and direction of the coast-line. The longer the "fetch," and the deeper the water, the higher the waves. A coast directly facing the prevalent wind will have larger waves than a neighbouring shore which presents itself at an angle to this wind or bends round so as to form a lee-shore. The highest waves in the narrow British seas probably never exceed 15 or 20 feet, and usually fall short of that amount. The greatest height observed by Scoresby among the Atlantic waves was 43 feet.[2]

Ground-swell propagated across a broad and deep ocean produces by far the most imposing breakers. So long as the water remains deep and no wind blows, the only trace of the passing ground-swell on the open sea is the huge broad heaving of the surface. But where the water shallows, the superficial part of the swell, travelling faster than the lower which encounters the friction of the bottom, begins to curl and crest as a huge billow or wall of water, that finally bursts against the shore. Such billows, even when no wind is blowing, often cover the cliffs of the north of Scotland with sheets of water and foam up to heights of 100 or even nearly 200 feet. During north-westerly gales, however, the windows of the Dunnet Head lighthouse, at a height of upwards of 300 feet above high-

[1] The student may consult Maury's "Physical Geography of the Sea," but more particularly Dr. Carpenter's papers in the *Proceedings of the Royal Society* for 1869-73, and *Journal of Royal Geographical Society* for 1871-77, on the side of temperature; and Herschel's "Physical Geography," and Croll's "Climate and Time," on the side of the winds.

[2] *Brit. Assoc. Rep.* 1850, p. 26. A table of the observed heights of waves round Great Britain is given in Mr. T. Stevenson's treatise on "Harbours," p. 20.

water mark, are said to be sometimes broken by stones swept up the cliffs by the sheets of sea-water which then deluge the building.

A single roller of the ground-swell 20 feet high falls, according to Mr. Scott Russell, with a pressure of about a ton on every square foot. Mr. Thomas Stevenson conducted some years ago a series of experiments on the force of the breakers on the Atlantic and North Sea coasts of Britain. The average force in summer was found in the Atlantic to be 611 lb. per square foot, while in winter it was 2086 lb., or more than three times as great. But on several occasions, both in the Atlantic and North Sea, the winter breakers were found to exert a pressure of three tons per square foot, and at Dunbar as much as three tons and a half.[1] Besides the waves produced by ordinary wind action, others of an extraordinary size and destructive power are occasionally caused by a violent cyclone-storm. The mere diminution of atmospheric pressure in a cyclone must tend to raise the level of the ocean within the cyclone limits. But the further furious spiral in-rushing of the air towards the centre of the low pressure area drives the sea onward, and gives rise to a wave or succession of waves having great destructive power. Thus, on 5th October, 1864, during a great cyclone which passed over Calcutta, the sea rose in some places 24 feet, and swept everything before it with irresistible force, drowning upwards of 48,000 people.

Besides the height and force of waves it is important to know the depth to which the sea is affected by such superficial movements. The Astronomer-Royal states that ground-swell may break in 100 fathoms water.[2] It is common to find boulders and shingle disturbed at a depth of 10 fathoms, and even driven from that depth to the shore, and waves may be noticed to become muddy from the working up of the silt at the bottom when they have reached water of 7 or 8 fathoms in depth.[3] It is stated by Delesse that engineering operations have shown that submarine constructions are scarcely disturbed at a greater depth than 5 metres (16·4 feet) in the Mediterranean and 8 metres (26·24 feet) in the Atlantic.[4] In the Bay of Gascony it has been ascertained that the depth at which the sea breaks and is effective in the transport of sand along the bottom varies from scarcely 3 metres in ordinary weather, to 5 metres in stormy weather, and only exceeds 10 metres (32·8 feet) in great hurricanes. According to Commander Cialdi, the movement of waves may disturb fine sand on the bottom at a depth of 40 metres (131 feet) in the English Channel, 50 metres (164 feet) in the Mediterranean, and 200 metres (656 feet) in the ocean.[5]

(4.) *Ice on the Sea.*—In this place may be most conveniently

[1] T. Stevenson, *Trans. Roy. Soc. Edin.* xvi. p. 25; treatise on "Harbours," p. 42.

[2] *Encyclopedia Metropolitana*, art. "Waves." Gentle movement of the bottom water is said to be sometimes indicated by ripple-marks on the fine sand of the sea-floor at a depth of 600 feet.

[3] T. Stevenson's "Harbours," p. 15.

[4] "Lithologie des Mers de France" (1872), p. 110.

[5] Quoted by Delesse, *op. cit.* p. 111.

noticed the origin and movements of the ice which in circumpolar latitudes covers the sea. This ice is derived from two sources—*a*, the freezing of the sea itself, and *β*, the seaward prolongation of land-ice.

a. Three chief types of sea-ice have been observed. (*a.*) In the Arctic sounds and bays the littoral waters freeze along the shores and form a cake of ice which, upborne by the tide and adhering to the land, is thickened by successive additions below, as well as by snow above, until it forms a shelf of ice 120 to 130 feet broad and 20 to 30 feet high. This shelf, known as the ice-foot, serves as a platform on which the abundant débris, loosened by the severe frosts of an Arctic winter, gathers at the foot of the cliffs. It is more or

Fig. 157.—Disrupted Floe-ice of Arctic Seas.

less completely broken up in summer, but forms again with the early frosts of the ensuing autumn. (*b.*) The surface of the open sea likewise freezes over into a continuous solid sheet, which, when undisturbed, becomes in the Arctic regions about eight feet thick, but which in summer breaks up into separate masses, sometimes of large extent, and is apt to be piled up into huge, irregular heaps. This is what navigators term *floe-ice*, and the separate floating cakes are known as *floes*. Ships fixed among these floes have been drifted with the ice for hundreds of miles until at last liberated by its disruption. (*c.*) In the Baltic Sea, off the coast of Labrador and elsewhere, ice has been observed to form on the sea-bottom.

It is known as ground-ice or anchor ice. In the Labrador fishing-grounds it forms even at considerable depths. Seals caught in the lines at those depths are said to be brought up sometimes solidly frozen.

β. In the Arctic regions vast glaciers drain the snow-fields, and, descending to the sea, extend for some distance from shore until large fragments break off and float away seawards. These detached

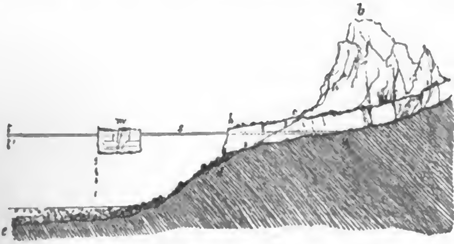
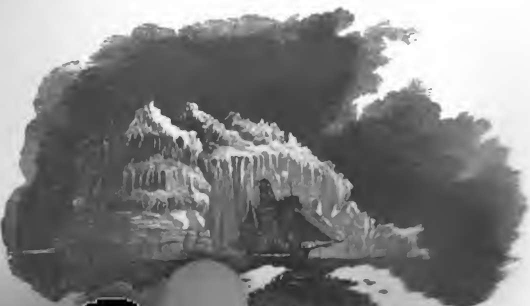


FIG. 158.—FORMATION OF ICEBERGS (*B.*).

The glacier (*a*, *h*) descends from mountainous ground (*b*) to the sea level (*s*), bearing moraine stuff on the surface, pushing on detritus below (*d*), and sending off icebergs (*m*), which may carry detritus and drop it over the sea-bottom; *t*, *t′*, *g*, lines of high and low water.

masses are icebergs. Their shape and size greatly vary, but lofty peaked forms are common, and they sometimes rise from 200 to 300 feet above the level of the sea. As only about an eighth part of the



above water.[1] Icebergs of the largest size consequently require water of some depth to float them, but are sometimes seen aground. In the Antarctic regions, where one vast sheet of ice envelopes the land and protrudes into the sea as a long, lofty rampart of ice, the detached icebergs often reach a great size, and are characterized by the frequency of a flat tabular form (Fig. 160).

Fig. 160.—Tabular Iceberg detached from the Great Antarctic Ice-barrier. (Wilkes.)

II. Geological Work. (1.) Influence on Climate.—Were there no agencies in nature for distributing temperature, there would be a regular and uniform diminution in the mean annual temperature from equator to poles, and the *isothermal* lines, or lines of equal heat, would coincide with lines of latitude. But no such general correspondence actually exists. A chart of the globe with the isothermal lines drawn across it, shows that their divergences from the parallels are striking, and most so where they approach and cross the ocean. Currents from warm regions raise the temperature of the tracts into which they flow; those from cold regions lower it. The ocean, in short, is the great distributor of temperature over the globe. As an illustration the two opposite sides of the North Atlantic may be taken. The cold Arctic current flowing southward along the north-east coast of America reduces the mean annual temperature of that region. On the other hand, the Gulf Stream brings to the shores of the north-west of Europe a temperature much above what they would otherwise enjoy. Dublin and the south-eastern headlands of Labrador lie on the same parallel of latitude, yet differ as much as 18° in their mean annual temperature, that of Dublin being 50°, and that of Labrador 32° Fahr. Dr. Croll has calculated that the Gulf Stream conveys nearly half as much heat from the tropics as is received from the sun by the entire Arctic regions.[2]

(2.) Erosion. A. *Chemical.*—The chemical action of the sea upon the rocks of its bed and shores has not yet been properly studied.[3]

[1] On flotation of Icebergs, see *Geol. Mag.* (2nd sec.), iii. pp. 303, 379; iv. 65, pp. 135.
[2] See a series of papers by him on the "Gulf Stream and Ocean Currents" in *Geol. Mag.* and *Phil. Mag.* for 1869, 1870–74, and his work "Climate and Time."
[3] See Bischof's "Chemical Geology," vol. i. chap. vii.

It is evident, however, that changes analogous to those effected by fresh water on the land must be in progress. Oxidation, and the formation of carbonates, no doubt continually take place. We may judge indeed of the nature and rapidity of some of these changes by watching the decay of stones and material employed in the construction of piers. Mr. Mallet—as the result of experiments with specimens sunk in the sea—concluded that from $\frac{3}{10}$ to $\frac{4}{10}$ of an inch in depth in iron castings 1 inch thick, and about $\frac{6}{10}$ of an inch of wrought iron, will be destroyed in a century in clear salt water. Mr. Stevenson, in referring to these experiments, remarks that at the Bell Rock lighthouse, twenty-five different kinds and combinations of iron were exposed to the action of the sea, and all yielded to corrosion. In some of these castings the loss has been at the rate of an inch in a century. "One of the bars which was free from air-holes had its specific gravity reduced to 5·63, and its transverse strength from 7409 lb. to 4797 lb., and yet presented no external appearance of decay. Another apparently sound specimen was reduced in strength from 4068 lb. to 2352 lb., having lost nearly half its strength in fifty years."[1] Similar results were recently observed by Mr. Grothe, resident engineer at the construction of the ill-fated railway bridge across the Firth of Tay. A cast-iron cylinder (such as was employed in constructing the concrete basements for the piers), which had been below water for only sixteen months, was found to be so corroded that a penknife could be stuck through it in many places. An examination of the shore will sometimes reveal a good deal of quiet chemical change on the outer crust of wave-washed rocks. Basalt, for instance, has its felspar decomposed, and shows the presence of carbonates by effervescing briskly with acid. The augite is occasionally replaced by ferrous carbonate.

B. *Mechanical.*—It is mainly by its mechanical action that the sea accomplishes its erosive work. This can only take place where the water is in motion, and, other things being equal, is greatest where the motion is strongest. Hence we cannot suppose that erosion to any appreciable extent can be effected in the abysses of the sea, where the only motion possible is the slow creeping of the polar water. But where the currents are powerful enough to move grains of sand and gravel, a slow erosion may take place even at considerable depths. It is in the upper portions of the sea, however, —the region of currents, tides, and waves,—that mechanical erosion is chiefly performed. The depth to which the influence of waves and ground-swell may extend seems to vary greatly according to the situation (*ante*, p. 423). A good test for the absence of serious abrasion is furnished by the presence of fine mud on the bottom. Wherever that is found, we may be tolerably sure that the bottom at that place lies beyond the reach of ordinary breaker action.[2] From the superior limit of the accumulation of mud up to high-water mark, and in exposed places up to 100 feet or more above high-water mark,

[1] T. Stevenson on "Harbours," p. 47.

[2] *Ibid.* p. 15.

lies the zone within which the sea does its work of abrasion. To this zone, even where the breakers are heaviest, a greater extreme vertical range can hardly be assigned than 300 feet, and in most cases it probably falls far short of that extent.

The mechanical work of erosion by the sea is done in four ways.

a. The enormous force of the breakers suffices to tear off fragments of the solid rocks. Abundant examples are furnished by the precipitous shores of Caithness, and of the Orkney and Shetland Islands. It sometimes happens that demonstration of the height to which the effective force of breakers may reach is furnished at lighthouses built on exposed parts of the coast. Thus, at Unst, the most northerly point of Shetland, walls were overthrown and a door was broken open at a height of 196 feet above the sea. At the Bishop Rock lighthouse, on the West of England, a bell weighing 3 cwt. was wrenched off at a level of 100 feet above high-water mark.[1] Some of the most remarkable instances of the power of breakers have been observed by Mr. Stevenson among the islands of the Shetland group. On the Bound Skerry he found that blocks of rock up to 9½ tons in weight had been washed together at a height of nearly 60 feet above the sea, that blocks weighing from 6 to 13½ tons had been actually quarried out of their original bed, at a height of from 70 to 75 feet, and that a block of nearly 8 tons had been driven before the waves at the level of 20 feet above the sea, over very rough ground, to a distance of 73 feet. He likewise records the moving of a 50-ton block by the waves at Barrahead, in the Hebrides.[2] At Plymouth, also, blocks of several tons in weight have been known to be washed about the breakwater like pebbles.[3]

β. The alternate compression and expansion of air in crevices of rocks exposed to heavy breakers dislocates large masses of stone, even above the direct reach of the waves. It is a fact familiar to engineers that, even from a vertical and apparently perfectly solid wall of well-built masonry exposed to heavy seas, stones will sometimes be started out of their places, and that when this happens a rapid enlargement of the cavity may be effected, as if

[1] T. Stevenson, *op. cit.* p. 31. D. A. Stevenson, *Min. Proc. Inst. Civ. Engin.* xlvi. (1876), p. 7. [2] T. Stevenson, *op. cit.* pp. 21–37.

[3] The student will bear in mind that the relative weight of bodies is greatly reduced when in water, and still more in sea-water. The following examples will illustrate this fact (T. Stevenson's "Harbours," p. 107):—

—	Specific Gravity.	No. of cubic feet to a ton in air.	No. of feet to a ton in sea-water of specific gravity 1·028.
Basalt	2·99	11·9	18·26
Red granite	2·71	13·2	21·30
Sandstone	2·41	14·8	26·00
Cannel Coal	1·54	23·3	70·00

the walls were breached by a severe bombardment. At the Eddystone lighthouse, during a storm in 1840, a door which had been securely fastened against the force of the surf from without, was actually driven outward by a pressure acting from within the tower, in spite of the strong bolts and hinges, which were broken. We may infer that, by the sudden sinking of a mass of water hurled against the building, a partial vacuum was formed, and that the air inside forced out the door in its efforts to restore the equilibrium.[1] This explanation may partly account for the way in which the stones are started from their places in a solidly built sea-wall. But besides this cause we must also consider a perhaps still more effective one in the condensation of the air driven before the wave between the joints and crevices of the stones, and its subsequent instantaneous expansion when the wave drops. During gales, when large waves are driven to shore, many tons of water are poured suddenly into a cleft or cavern. These volumes of water, as they rush in, compress the air into every joint and pore of the rock at the further end, and then quickly retiring, exert such a suction as from time to time to bring down part of the walls or roof. The sea may thus gradually form an inland passage for itself to the surface above, in a "blow-hole" or "puffing-hole," through which spouts of foam and spray are in storms shot high into the air. On the more exposed portions of the west coast of Ireland numerous examples of such blow-holes occur. In Scotland, likewise, they may often be observed, as in the Bullers (boilers) of Buchan on the coast of Aberdeenshire, and the Geary Pot near Arbroath. Magnificent instances occur among the Orkney and Shetland Islands, some of the more shattered rocks of these northern coasts being, as it were, honeycombed by sea-tunnels, many of which open up into the middle of fields or moors.

γ. The hydraulic pressure of those portions of large waves that enter fissures and passages tends to force asunder masses of rock. The sea-water which, as part of an in-rushing wave, fills the gullies and chinks of the shore-rocks exerts the same pressure upon the walls between which it is confined as the rest of the wave is doing upon the face of the cliff. Each cleft so circumstanced becomes a kind of hydraulic press, the potency of which is to be measured by the force with which the waves fall upon the rocks outside—a force which often amounts to three tons on the square foot. There can be little doubt that by this means considerable pieces of a cliff are from time to time dislodged.

δ. The waves make use of the loose detritus within their reach to break down cliffs exposed to their fury. Probably by far the largest amount of erosion is thus accomplished. The blows dealt against shore-cliffs by boulders, gravel, and sand swung forward by breakers, were aptly compared by Playfair to a kind of artillery.[2] During a storm upon a shingly coast we may hear, at a distance of

[1] Walker, *Proc. Inst. Civ. Engin.* i. p. 15; Stevenson's "Harbours," p. 10.
[2] "Illustrations of the Huttonian Theory," sec. 97.

several miles, the grind of the stones upon each other, as they are dragged back by the recoil of the waves which had launched them forward. In this tear and wear the loose stones are ground smaller, and acquire the smooth round form so characteristic of a surf-beaten beach. At the same time they bruise and wear down cliffs against which they are driven. A rock much jointed, or from any cause presenting less resistance to attack, is excavated into gullies, creeks, and caves; its harder parts standing out as promontories are pierced; gradually a series of detached buttresses and sea-stacks appears as the cliff recedes, and these in turn are wasted until they become mere skerries and sunken surf-beaten reefs (Fig. 161). At the same time the surface of the beach is ground down. The reality of this erosion and consequent lowering of level is sometimes instructively displayed where a block of harder rock serves for a time to pro-

Fig. 161.—Coast of Cornwall, at Bedruthan (Devonian Rocks), cut by the Sea into Cliffs, Bays, and Stacks (*B.*).

tect the portion of rocky beach lying beneath it. The block by degrees comes to rest on a growing pedestal which is eventually cut round by the waves, until the overlying mass, losing its support, rolls down upon the beach, and the same process is renewed (Fig. 162).

Of the progress of marine erosion the more exposed parts of the British coast-line furnish many admirable examples. The west coast of Ireland, exposed to the full swell of the Atlantic, is in innumerable localities completely undermined by caverns, into which the sea enters from both sides. The precipitous coasts of Skye, Sutherland, Caithness, Forfar, Kincardine, and Aberdeenshire abound in the most impressive lessons of the waste of a rocky sea-margin; while the same picturesque features are prolonged into the Orkney and Shetland Islands, the magnificent cliffs of Hoy towering as a vast wall some 1200 feet above the Atlantic breakers, which are tunnelling and fretting their base.

If such is the progress of waste where the materials consist of the most solid rocks, we may expect to meet with still more impressive proofs of decay where the coast-line can oppose only soft sand or clay to the march of the breakers. Again, the geological

FIG. 162.—BOULDER OF BASALT PROTECTING THE PORTION OF BEACH UNDERNEATH IT; LARGO, FIFE.

student in Britain can examine for himself many illustrations of this kind of destruction around the shores of these islands. Within the last few hundred years entire parishes with their towns and villages have been washed away, and the tide now ebbs and flows over districts which in old times were cultivated fields and cheerful hamlets. The coast of Yorkshire between Flamborough Head and the mouth of the Humber, and also that between the Wash and the mouth of the Thames, suffer at a specially rapid rate, for the cliffs in these parts consist in great measure of soft clay. In some places this loss is said to amount to 3 feet per annum.

While investigating the progress of waste along a coast-line, the geologist has to consider the varying powers of resistance possessed by rocks, and the extent to which the action of the waves is assisted by that of the subaerial agents. Rocks of little tenacity and readily susceptible of disintegration, obviously present least resistance to the advance of the waves. A clay, for example, is readily eaten away. If, however, it should contain numerous hard nodules or imbedded boulders, these, as they drop out, may accumulate in front beneath the cliff, and serve as a partial breakwater against the waves (Fig. 163). On the other hand, a hard band or boss of rock may withstand the destruction which overtakes the softer or more jointed surrounding portions, and may consequently be left projecting into the sea, as a line of headland or promontory, or rising as an isolated stack (Fig. 161). But besides mere hardness or softness, the

geological structure of the rocks powerfully influences the nature and rate of the encroachment of the sea. Where, owing to the inclination of bedding, joints, or other divisional planes, sheets of rock slope down into the water, they serve as a kind of natural breakwater, up

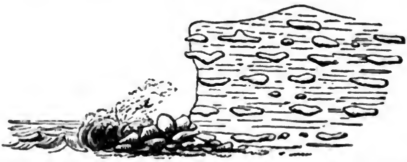


Fig. 163.—Cliffs of Clay full of Septarian Nodules, the accumulation of which serves to arrest the progress of the Waves.

and down which the surges rise and fall during calms, or rush in crested billows during gales, the abrasion being here reduced to the smallest proportions. In no part of the degradation of the land, can the dominant influence of rock-structure be more conspicuously observed and instructively studied, than along marine cliffs. Where the lines of precipice are abrupt, with numerous projecting and retiring vertical walls, it will almost invariably be found, that these perpendicular faces have been cut open along lines of intersecting joint. The existence of such lines of division permits a steep or vertical front to be presented by the land to the sea, because, as slice after slice is removed, each freshly bared surface is still defined by a joint-plane. (See Book IV., Sect. ii.)

But during the study of any rocky coast where these features are exhibited, the observer will soon perceive that the encroachment of the sea upon the land is not due merely to the action of the waves, but that even on shores where the gales are fiercest and the breakers most vigorous, the demolition of the cliffs depends mainly upon the sapping influence of rain, springs, frosts, and general atmospheric disintegration. In Fig. 164, for example, which gives a view of a portion of the northern Caithness coast, exposed to the full fury of the gales and rapid tidal currents which rush from the Atlantic through the Pentland Firth, we see at once that though the base of the cliff is scooped out by the restless surge into long twilight caves, nevertheless the recession of the precipice is caused by the wedging off of slice after slice, along the lines of vertical joint, and that this process begins at the top, where the subaerial forces and not the waves are the sculptors. Undoubtedly the sea plays its part by removing the materials dislodged, and preventing them from accumulating against and protecting the face of the precipice. But were it not for the potent influence of subaerial decay, the progress of the sea would be comparatively feeble. The very blocks of stone which give the waves so much of their efficacy as abrading agents, are in great measure furnished to them by the action of the meteoric

agents. If sea-cliffs were mainly due to the destructive effects of the waves, they ought to overhang their base, for at or near their

FIG. 164.—VERTICAL SEA-CLIFFS OF FLAGSTONE, NEAR HOLBURN HEAD, CAITHNESS.

base only does the sea act (Fig. 165). But the fact that in the vast majority of cases sea-cliffs, instead of overhanging, slope backward, at a greater or less angle, from the sea (Fig. 161),

FIG. 165.—MARINE EROSION WHERE EXCEPTIONALLY THE BASE OF A CLIFF RECEDES FASTER THAN THE UPPER PART.

shows that the waste from subaerial action is really greater than that from the action of the breakers.[1] Even when a cliff actually overhangs, however, it may often be shown that the apparent greater recession of its base, and inferentially the more powerful denuding

[1] Whitaker, *Geol. Mag.* iv. p. 447.

action of the sea, are deceptive. In Fig. 166, one of innumerable examples from the Old Red Sandstone cliffs of Caithness and the Orkney and Shetland Islands, we at once perceive that the process of demolition is precisely similar to that already cited in Fig. 164. The cliff recedes by the loss of successive slices from its sea-front, which are wedged off not by the waves below, but by the subaerial agents above, along lines of parallel joint. To the inclination of these divisional planes at a high angle from the sea, the precipice owes its slope towards the land.

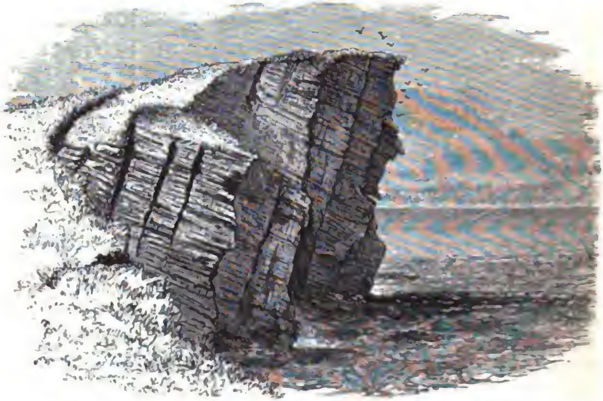


Fig. 166.—Overhanging Cliff, Brough of Birsa, Orkney.

Ice erosion.—Among the erosive operations of the sea must be included what is performed by floating ice. Along the margin of Arctic lands a good deal of work is done by the broken-up floe-ice and ice-foot. These cakes of ice, driven ashore by storms, tear up the soft shallow-water or littoral deposits, rub and scratch the rocks, and push gravel and blocks of rock before them as they strand on the beach. Icebergs also, when they get aground in deep water, must greatly disturb the sediment accumulating there, and may grind down any submarine rock on which they grate as they are driven along. The geological operations of floating ice were formerly invoked by geologists to explain much that is now believed to have been entirely the work of ice on land.

(3.) Transport.—By means of its currents the sea transports mechanically suspended sediment to varying distances from the land. The distance will depend on the size, form, and specific gravity of the sediment on the one hand, and on the velocity and transporting power of the marine current on the other. Babbage estimated that if from the mouth of a river 100 feet deep, suspended limestone

mud of different degrees of fineness, were discharged into a sea having a uniform depth of 1000 feet over a great extent, four varieties of silt falling respectively through 10, 8, 5, and 4 feet of water per hour would be distributed as in the following table.[1]

No.	Velocity of fall per hour.	Nearest distance of deposit to river.	Length of deposit.	Greatest distance of deposit from river.
	feet.	miles.	miles.	miles.
1.	10	180	20	200
2.	8	225	25	250
3.	5	360	40	400
4.	4	450	50	500

It must be borne in mind, however, that mechanical sediment sinks faster in salt than in fresh water.[2] The fine mud in the layer of river water which floats for a time on the salter and heavier sea-water begins to sink more rapidly as soon as the two waters commingle.

Near the land, where the movements of the water are active, much coarse detritus is transported along shore or swept farther out to sea. A prevalent wind, by creating a current in a given direction, or a strong tidal current setting along a coast-line, will cause the shingle to travel coastwise, the stones getting more and more rounded and reduced in size as they recede from the sources. The Chesil Bank, which runs as a natural breakwater 16 miles long connecting the Isle of Portland with the mainland of Dorsetshire, consists of rounded shingle which is constantly being driven westwards. On the Moray Firth the reefs of quartz-rock about Cullen furnish abundance of shingle, which, urged by successive easterly gales, moves westwards along the coast for more than fifteen miles. The coarser sediment probably seldom goes much beyond the littoral zone. From a depth of even 600 fathoms in the North Atlantic between the Faroe Islands and Scotland small pebbles of volcanic and other rocks are dredged up which may have been carried by an Arctic under-current from the north. But recently Mr. Murray and Captain Tizzard have brought up large blocks of rounded shingle from the bank (300 fathoms) between Scotland and Faroe. This coarse detritus can hardly be due to any present action of the sea, for at such depths the force of currents at the bottom must be too feeble to push along coarse shingle. It may be glacial detritus dating back to the Glacial Period. Much fine sediment is carried in suspension by the sea for long distances from land. The Amazon pours so much silt into the sea as to discolour it for several hundred miles. After wet weather the sea around the shores of the British Islands is sometimes made turbid by the quantity of mud washed by rain

[1] *Q. J. Geol. Soc.* xii. 368.
[2] For a suggested explanation of this fact see Ramsay, *Q. J. Geol. Soc.* xxxii. p. 129.

and streams from the land. Dr. Carpenter found the bottom waters of the Mediterranean to be everywhere permeated by an extremely fine mud, derived no doubt from the rivers and shores of that sea. He remarks that the characteristic blueness of the Mediterranean, like that of the Lake of Geneva, may be due to the diffusion of exceedingly minute sedimentary particles through the water.

During the voyage of the *Challenger*, from the abysses of the Pacific Ocean, at remote distances from land, the dredge brought up bushels of rounded pieces of pumice of all sizes up to blocks a foot in diameter. These fragments were all evidently water-worn, as if derived from land, though we are still ignorant of the extent to which they may have been supplied by submarine volcanic eruptions. Some small pieces were taken on the surface of the ocean in the tow-net. Round volcanic islands, and off the coasts of volcanic tracts of the mainland, the sea is sometimes covered with floating pieces of water-worn pumice swept out by flooded rivers. These fragments may drift away for hundreds or even thousands of miles until, becoming water-logged, they sink to the bottom. The universal distribution of pumice was one of the most noticeable features in the dredgings of the *Challenger*. The clay which is found on the bottom of the ocean at the greatest distances from any shore contains only volcanic minerals and appears to be due to the trituration of volcanic detritus. At a distance of several hundred miles from shore traces of the minerals of the crystalline rocks of the land begin to make their appearance.[1]

Another not unimportant process of marine transport is that performed by floating ice. Among the Arctic glaciers moraine stuff is of rare occurrence; but occasional blocks of rock and heaps of earth and stones fall from the cliffs which rise above the general waste of snow. Hence on the icebergs that float off from these glaciers, rock débris may sometimes be observed. It is transported southward for hundreds of miles until, by the shifting or melting of the bergs, it is dropped into deep water. The floor of certain portions of the North Atlantic in the pathway of the bergs may be plentifully strewn with this kind of detritus. By means of the ice-foot also, an enormous quantity of earth and stones is every year borne away from the shore by the disrupted ice, and is strewn over the floor of the sounds, bays, and channels.

(4.) Reproduction.—The sea, being the receptacle for the material worn away from the land, must receive and store up in its depths all that vast amount of detritus by the removal of which the level and contours of the land are in the course of time so greatly changed. The deposits which take place within the area covered by the sea may be divided into two groups—the inorganic and organic. It is the former with which we have at present to deal; the latter will be discussed with the other geological functions of plants and

[1] Murray, *Proc. Roy. Soc. Edin.* 1876-7, p. 217.

animals (see p. 461, *seq.*). The inorganic deposits of the sea-floor are (1) chemical and (2) mechanical.

i. Of Chemical deposits now forming on the sea-floor we know as yet very little. At the mouth of the Rhone a crystalline calcareous deposit accumulates in which the débris of the sea-floor is enveloped. As sea-water contains so minute a proportion of carbonate of lime and so much larger a proportion of carbon dioxide than is needed to keep this carbonate in solution, Bischof estimated that no precipitation of carbonate of lime could take place from sea-water until after $\frac{17}{18}$ of the water had evaporated.[1] It is thus evident that no deposit of lime in the open sea is possible from concentration of sea-water. But the calcareous formation on the sea-bottom opposite rivers like the Rhone may be explained by supposing that as the layer of river water floats and thins out over the surface of the sea in warm weather with rapid evaporation, its comparatively large proportion of carbonate of lime may be partially precipitated. It has been observed near Nice, as well as on the African coast and other parts of the Mediterranean shores, that the shore rocks within reach of the water have a hard varnish-like crust deposited upon them. This substance consists essentially of carbonate of lime. As it extends over rocks of the most various composition, it is probably due to a deposit of lime held in solution in the shore sea-water, and rapidly evaporated in pools or while bathing the surface of rocks exposed to strong sun-heat.[2]

During the researches of the *Challenger* expedition, important facts in the history of marine chemistry have been obtained from the abysses of the Atlantic and Pacific oceans. Some of these are referred to on pp. 441, 469.

ii. The Mechanical deposits of the sea may be grouped into subdivisions according as they are directly connected with the waste of the land, or have originated at great depths and remote from land, when their source is not so obvious.

A. *Land-derived or Terrigenous.*—These may be conveniently grouped according to their relative places on the sea-bed.

a. Shore Deposits.—The most conspicuous and familiar are the layers of gravel and sand which accumulate between tide-marks. As a rule, the coarse materials are thrown up about the upper limit of the beach. They seem to remain stationary there; but if watched and examined from time to time, they will be found to be continually shifted by high tides and storms, so that the bank or bar of shingle retains its place though its component pebbles are being constantly moved. During gales coincident with high tides, coarse gravel may be piled up considerably above the ordinary limit of the waves in the form of what are termed *storm-beaches.*[3] Below the limit of coarse shingle upon the beach lies the zone of fine gravel, and then that of

[1] *Chem. Geol.* i. p. 178.
[2] *Bull. Soc. Géol. France* (3), ii. p. 219, iii. p. 46, vi. p. 84.
[3] See Kinahan on Sea-beaches, *Proc. Roy. Irish Acad.* (2nd. ser.), iii. p. 101.

sand, the sediment, though liable to irregular distribution, yet tending to arrange itself according to coarseness and specific gravity, the rougher and heavier detritus lying at the upper, and the finer and lighter towards the lower edge of the shore. The nature of the littoral accumulations on any given part of a coast-line must depend either upon the character of the shore-rocks which at that locality are broken up by the waves, or upon the set of the shore-currents, and the kind of detritus they bear with them. Coasts exposed to heavy surf, especially where of a rocky character, are apt to present beaches of coarse shingle between their projecting promontories. Sheltered bays, on the other hand, where wave-action is comparatively feeble, afford a gathering ground for finer sediment such as sand and mud. Estuaries and inlets into which rivers enter frequently show wide muddy flats at low water. Deposits of comminuted shells, coral-sand, or other calcareous organic remains thrown up on shore, may be cemented into compact rock by the solution and redeposit of carbonate of lime (p. 324). Where tidal currents sweep along a coast yielding much detritus, long bars or shoals may form parallel with the shore. On these the shingle and sand are driven coastwise in the direction of the prevalent current.[1]

β. Infra-Littoral and Deeper-Water Deposits.—These extend from below low-water mark to a depth of sometimes as much as 2000 fathoms, and reach a distance from land varying up to 200 miles or even more. Near land, and in comparatively shallow water, they consist of banks or sheets of sand, more rarely mixed with gravel. The bottom of the North Sea, for example, which between Britain and the continent of Europe lies at a depth never reaching 100 fathoms, is irregularly marked by long ridges of sand enclosing here and there hollows where mud has been deposited. In the English Channel large banks of gravel extend through the Straits of Dover as far as the entrance to the North Sea. These features seem to indicate the line of the chief mud-bearing streams from the land, and the general disposition of currents and eddies in the sea which covers that region, the gravel ridges marking the tracts or junctions of the more rapidly moving currents, while the muddy hollows point to the eddies where the fine sediment is permitted to settle on the bottom. It is possible, however, that the inequalities on the floor of the North Sea, and their peculiarities of sediment, are not wholly modern, but may be partly due to irregular deposition of glacial drift and partly to the contour of the ground before it was submerged and the land connection between Britain and Europe was destroyed.

During the course of the voyage of the *Challenger*, the approach to land could always be foretold from the character of the bottom, even at distances of 150 and 200 miles. The deposits were found to consist of blue and green muds derived from the degradation of older crystalline rocks. At depths of 100 to 700

[1] See Bristow and Whitaker on Chesil Bank, Dorset, *Geol. Mag.* (1869), vi. p. 433; Kinahan, *Geol. Mag.* (Decade 2.) (1874), i.

fathoms they are often coloured green by glauconite. At greater depths they consist of blue or dark slate-coloured mud with a thin upper red or brown layer. Throughout these land-derived sediments particles of mica, quartz, and other minerals are distributed, the materials becoming coarser towards land. Pieces of wood, portions of fruits, and leaves of trees occur in them, and further indicate the reality of the transport of material from the land. Shells of pteropods, larval gasteropods, and lamellibranchs are tolerably abundant in these muds, with many infra-littoral species of *Foraminifera*, and diatoms. Below 1500 or 1700 fathoms pteropod shells seldom appear, while at 3000 fathoms hardly a foraminifer or any calcareous organism remains.[1] Round volcanic islands the bottom is found to be covered with grey mud and sand derived from the degradation of volcanic rocks. These deposits can be traced to great distances; from Hawaii they extend for 200 miles or more. Pieces of pumice, scoriæ, &c., occur in them, mingled with marine organisms, and more particularly with abundant grains, incrustations, and nodules of an earthy peroxide of manganese. Near coral-reefs the sea-floor is covered with a white calcareous mud derived from the abrasion of coral. The east coast of South America supplies a peculiar red mud which is spread over the Atlantic slope down to depths of more than 2000 fathoms.

B. *Abysmal.*—Passing over at present the organic deposits which form so characteristic a feature on the floor of the deeper and more open parts of the ocean, we come to certain red and grey clays found at depths of more than 2000 fathoms down to the bottoms of the deepest abysses. These, by far the most wide-spread of oceanic deposits, consist of exceedingly fine clay, coloured sometimes red by iron-oxide, sometimes of a chocolate tint from manganese oxide, with grains of augite, felspar, and other volcanic minerals, pieces of palagonite and pumice, nodules of peroxide of manganese, and other mineral substances, together with *Foraminifera*, and in some regions a large proportion of siliceous *Radiolaria*. These clays seem to result from the decomposition of pumice and fine volcanic dust transported from volcanic islands into mid-ocean,[2] or from the accumulation of the detritus of submarine eruptions. The absence in them of obviously land-derived non-volcanic minerals seems to point to an abundance of submarine volcanic action, of which as yet no other evidence has been obtained. The extreme slowness of deposit is strikingly brought out in the tracts of sea-floor farthest removed from land. From these localities great numbers of sharks' teeth, with ear-bones and other bones of whales, were dredged up in the *Challenger* expedition,—some of them quite fresh, others partially crusted with peroxide of manganese, and some wholly and thickly surrounded with that substance. We cannot suppose that sharks and whales so abounded in the sea at one time as to cover the floor of the ocean with a continuous

[1] Murray, *Proc. Roy. Soc.* 1876, p. 519.
[2] Murray, *op. cit.* and *Proc. Roy. Soc. Edin.* ix. p. 247.

stratum of their remains. No doubt each haul of the dredge which brought up so many bones represented the droppings of many generations. The successive stages of manganese incrustation point to a long, slow, undisturbed period, when so little sediment accumulated that the bones dropped at the beginning remained at the end still uncovered, or only so slightly covered as to be easily scraped up by the dredge. In these deposits, moreover, Mr. Murray has found numerous minute spherular particles of metallic iron which he regards as of cosmic origin—portions of the dust of meteorites which in the course of ages have fallen upon the sea-bottom. Such particles no doubt fall all over the ocean; but it is only on those parts of the bottom which, by reason of their distance from any land, receive accessions of deposit with extreme slowness—and where therefore the present surface may contain the dust of a long succession of years—that it may be expected to be possible to detect them.

The abundant deposit of peroxide of manganese over the floor of the deep sea is one of the most singular features of recent discovery. It occurs as an earthy incrustation round bits of pumice, bones, and other objects (Fig. 167). The nodules possess a concentric arrange-

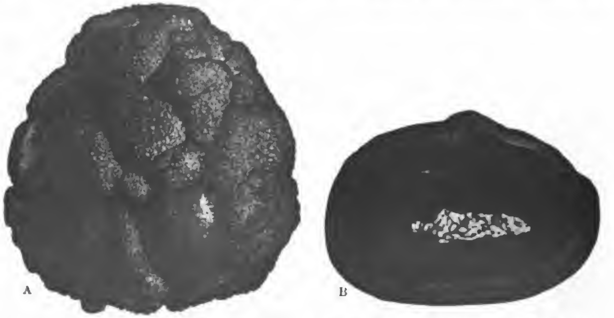


Fig. 167.—Manganese Nodules. Floor of the North Pacific. Two-thirds natural size.[1]

A, Nodule from 2900 fathoms showing external form. B, Section of nodule from 2740 fathoms showing internal concentric deposit round a fragment of pumice.

ment of lines not unlike those of urinary calculi. That they are formed on the spot, and not drifted from a distance, was made abundantly clear from their containing abysmal organisms, and enclosing more or less of the surrounding bottom, whatever its nature might happen to be. Quite recently Mr. J. Y. Buchanan has dredged similar small manganese concretions from some of the deeper parts of Loch

[1] From the Reports of the "Challenger" Expedition. The detailed investigation by Messrs. Murray and Renard of the deep-sea deposits obtained by this expedition will form one of the most important contributions yet made to our knowledge of the chemistry of the oceanic abysses.

Fyne.[1] The formation of such concretions may be analogous to the solution and deposition of oxides of iron and manganese by organic acids, as on lake floors, bogs, &c. (p. 463). In connection with the chemical reactions indicated by these nodules as taking place on the sea-bottom, reference may be made to a still more remarkable discovery made by Mr. Murray in the course of his examinations of the materials brought up from the same abysmal deposits. He has detected abundant minute concretions or bundles of crystals which on analysis by M. Renard have been identified with the zeolite known as phillipsite. These crystals have certainly been formed directly on the sea-bottom, for they are found gathered round abysmal organisms. The importance of this fact in reference to the chemistry of marine deposits is at once obvious.

From a comparison of the results of the dredgings made in recent years in all parts of the oceans, it is impossible to resist the conclusion that there is nothing in the character of the deep-sea deposits which finds a parallel among the marine geological formations visible to us on land. It is only among the comparatively shallow water accumulations of the existing sea that we encounter analogies to the older formations. And thus we reach by another and a new approach the conclusion which on very different grounds has been arrived at, viz., that the present continental ridges have existed from the remotest times, and that the marine strata which constitute so large a portion of their mass have been accumulated not as deep water formations, but in comparatively shallow water along their flanks.[2]

§ 7. DENUDATION AND DEPOSITION.—The results of the action of Air and Water upon Land.[3]

It may be of advantage, before passing from the subject of the geological work of water, to consider the broad results achieved by the co-operation of all the forces by which the surface of the land is worn down. These results naturally group themselves under the two heads of Denudation and Deposition.

1. *Subaerial Denudation—the general lowering of land.*

The true measure of denudation is to be sought in the amount of mineral matter removed from the surface of the land and carried into the sea. This is an appreciable and measurable quantity. There may be room for discussion as to the way in which the waste is to be apportioned to the different forces that have produced it, but the total amount of sea-borne detritus must be accepted as a fact

[1] *Nature*, xviii. (1878), p. 628.
[2] *Proc. Roy. Geograph. Soc.* July, 1879.
[3] This section is mainly taken from an essay by the author, *Trans. Geol. Soc. Glasgow*, iii. p. 153.

about which, when properly verified, no further question can possibly arise. In this manner the subject is at once disencumbered of difficulty in fixing the relative importance of rain, rivers, frost, glaciers, &c., considered as denuding agents. We have simply to deal with the sum-total of results achieved by all these forces acting severally and conjointly. Thus considered, this subject casts a new light on the origin of existing land-surfaces, and affords some fresh data for approximating to a measure of past geological time.

Of the mineral substances received by the sea from the land, vastly the larger portion is brought down by streams; a relatively small amount is washed off by the waves of the sea itself. It is the former, or stream-borne part, which is at present to be considered. The quantity of mineral matter carried every year into the ocean by the rivers of a continent represents the amount by which the general surface of that continent is annually lowered. Much has been written of the vastness of the yearly tribute of silt borne to the ocean by such streams as the Ganges and Mississippi; but "the mere consideration of the number of cubic feet of detritus annually removed from any tract of land by its rivers does not produce so striking an impression upon the mind as the statement of how much the mean surface-level of the district in question would be reduced by such a removal."[1] This method of inquiry is so obvious and instructive that it probably received attention from early geologists, though data were still wanting for its proper application. Playfair, for instance, in speaking of the transference of material from the surface of the land to the bottom of the sea, remarks that "the time requisite for taking away by waste and erosion two feet from the surface of all our continents and depositing it at the bottom of the sea, cannot be reckoned less than two hundred years."[2] This estimate does not appear to have been based on any actual measurements, and must greatly exceed the truth; but it serves to indicate how broad was the view that Playfair held of the theory which he undertook to illustrate. The first geologist who appears to have attempted to form any estimate on this subject from actually ascertained data, was Mr. Alfred Tylor, who, in the year 1850, published a paper in which he estimated the probable amount of solid matter annually brought into the ocean by rivers and other agents. He inferred that the quantity of detritus now distributed over the sea bottom every year would, at the end of 10,000 years, cause an elevation of the ocean-level to the extent of at least three inches.[3] The subject was afterwards taken up by Dr. Croll, who

[1] Tylor, *Phil. Mag.* 4th series, v. p. 268, 1850.

[2] "Illustrations," p. 424. Manfredi had previously made a calculation of the amount of rain that falls over the globe, and of the quantity of earthy matter carried into the sea by rivers. He estimated that this earthy matter distributed over the sea bed must raise the level of the latter five inches in 348 years. Von Hoff, "Veränderungen der Erdoberfläche," Band i. p. 232. See the other autuorities there cited.

[3] *Phil. Mag. loc. cit.*

specially drew attention to the Mississippi as a measure of denudation and thereby of geological time.[1]

When the annual discharge of mineral matter carried seaward by a river and the area of country drained by that river are both known, the one sum divided by the other gives the amount by which the drainage area has its mean general level reduced in one year. For it is clear that if a river carries so many millions of cubic feet of sediment every year into the sea, the area drained by it must have lost that quantity of solid material, and if we could restore the sediment so as to spread it over the basin, the layer so laid down would represent the fraction of a foot by which the surface of the basin had been lowered during a year.

It has been already shown that the material removed from the land by streams is twofold—one portion is chemically dissolved, the other is mechanically suspended in the water or pushed along the bottom. Properly to estimate the loss sustained by the surface of a drainage basin, we ought to know the amount of mineral matter removed in each of these conditions, and also the volume of water discharged, from measurements and estimates made at different seasons and extending over a succession of years. These data have not yet been fully collected from any river, though some of them have been ascertained with approximate accuracy, as in the Mississippi Survey of Messrs. Humphreys and Abbot, and the Danube Survey of the International Commission. As a rule, more attention has been shown to the amount of mechanically suspended matter than to that of the other ingredients. For the present, therefore, we may confine ourselves to this part of the earthy substances removed from the land by running water. It will be borne in mind, however, that the following estimates, in so far as they are based upon only one portion of the waste of the land, are under-statements of the truth.

The proportion of mineral substances held in suspension in the water of rivers has been already (p. 370) discussed. It was pointed out that it is most advantageous to determine the amount of mineral matter by weight, and then from its average specific gravity to estimate its bulk as an ingredient in river water. The proportion by weight is probably, on an average, about half that by bulk.

It may seem superfluous to insist that the earthy matter borne into the sea from any given area represents so much actual loss from the surface of that area. Yet this self-evident statement is probably not realized by many geologists to the extent which it deserves. If a stream removes in one year one million of cubic yards of earth from its drainage basin, that basin must have lost one million of cubic yards from its surface. From the data and authorities which have already been adduced (pp. 370, 371), the subjoined table has been constructed, in which are given the results of the measurement of the proportion of sediment in a few rivers. The last column shows

[1] *Phil. Mag.* for February 1867, and May 1868. See also his "Climate and Time." Geikie, *Geol. Mag.* June 1868; *Trans. Geol. Soc. Glasgow*, iii. p. 153.

the fraction of a foot of rock (reckoning the specific gravity of the silt at 1·9 and that of rock at 2·5) which each river must remove from the general surface of its drainage basin in one year.

Name of River.	Area of basin in square miles.	Annual discharge of sediment in cubic feet.	Fraction of foot of rock by which the area of drainage is lowered in one year.
Mississippi . .	1,147,000	7,459,267,200	$\frac{1}{6000}$
Ganges (Upper) .	143,000	6,368,077,440	$\frac{1}{823}$
Hoang Ho . .	700,000	17,520,000,000(?)	$\frac{1}{1464}$
Rhone. . . .	25,000	600,381,800	$\frac{1}{1528}$
Danube . . .	234,000	1,253,738,600	$\frac{1}{6846}$
Po	30,000	1,510,137,000	$\frac{1}{729}$

At the present rate of erosion, the rivers named in this table remove one foot of rock from the general surface of their basins in the following ratio:—The Mississippi removes one foot in 6000 years; the Ganges above Ghazipûr does the same in 823 years;[1] the Hoang Ho in 1464 years; the Rhone in 1528 years; the Danube in 6846 years; the Po in 729 years. If these rates should continue, the Mississippi basin will be lowered 10 feet in 60,000 years, 100 feet in 600,000 years, 1000 feet in 6,000,000. Assuming Humboldt's estimate of the mean height of the North American continent, 748 feet,[2] we find that at the Mississippi's rate of denudation, this continent would be worn away in about four and a half million years. The Ganges works still more rapidly. It removes one foot of rock in 823 years, and if Humboldt's estimate of the average height of the Asiatic continent be accepted, viz., 1132 English feet, that mass of land, worn down at the rate at which the Ganges destroys it, would be reduced to the sea-level in little more than 930,000 years. Still more remarkable is the extent to which the River Po denudes its area of drainage. Even though measurements had not been made of the ratio of sediment contained in its water, we should be prepared to find that proportion a remarkably large one if we look at the enormous changes which, within historic times, have been made by the alluvial accumulations of this river (p. 390). If the Po removes one foot of rock from its drainage basin in 729 years, it will lower that basin 10 feet in 7290 years, 100 feet in 72,900 years. If the whole of Europe (taken at a mean height of 671 feet) were denuded at the same rate, it would be levelled in rather less than half a million of years.

It is not pretended that these results are strictly accurate. On

[1] In my original paper the area of drainage of the Ganges was given as 432,480 square miles. But the area from which the annual discharge of silt was there given was only that part of the Gangetic basin above Ghazipûr, which Dr. Haughton estimates at 143,000 square miles (*Proc. Roy. Dublin Soc.* 1879, No. xxxix.). Hence, as he has pointed out, the rate of erosion is really much greater than I had made it. I have recalculated the rate from the altered data, and the result is as given above.

[2] *Ante*, p. 35.

the other hand they are not mere guesses. The amount of water flowing into the sea, and the annual discharge of sediment, have been in each case measured with greater or less precision. The areas of drainage may perhaps require to be increased or lessened. But though some change may be made upon the ultimate results just given, it is hardly possible to consider them attentively without being forced to ask whether those enormous periods which geologists have been in the habit of demanding for the accomplishment of geological phenomena, and more especially for the very phenomena of denudation, are not in reality far too vast. If the Mississippi is carrying on the process of denudation so rapidly that at the same rate the whole of North America might be levelled in four and a half millions of years, surely it is most unphilosophical to demand unlimited ages for similar but often much less extensive denudations in the geological past. Moreover, that rate of erosion appears on the whole to be rather below the average in point of rapidity. The Po, for instance, works more than eight times as fast. But as the physics of the Mississippi have been more carefully studied than those of perhaps any other river, and as that river drains so extensive a region, embracing so many varieties of climate, rock and soil, we shall probably not exaggerate the result if we assume the Mississippi ratios as an average. It is of course obvious that as the level of the land is lowered the rate of subaerial denudation decreases, so that on the supposition that no subterranean movements took place to aid or retard the denudation, the last stages in the demolition of a continent must be enormously slower than during earlier periods.

There is another point of view from which a geologist may advantageously contemplate the active denudation of a country. He may estimate the annual rainfall and the proportion of water which returns to the sea. If he can obtain a probable average ratio for the earthy substances contained in the river water which enters the sea, he will be able to estimate the mean amount of loss sustained by the whole country. Thus, taking the average rainfall of the British Islands at 36 inches annually, and the superficial area over which this rain is discharged at 120,000 square miles, then it will be found that the total quantity of rain received in one year by the British Isles is equal to about 68 cubic miles of water. If the proportion of rainfall returned to the sea by streams be taken at a third, there are 23 cubic miles; if at a fourth, there are 17 cubic miles of fresh water sent off the surface of the British Islands into the sea in one year. Assuming, in the next place, that the average ratio of mechanical impurities is only $\frac{1}{5000}$ by volume of the water, the proportion of the rainfall returned to the sea being $\frac{1}{4}$, then it will follow that $\frac{1}{8800}$ of a foot of rock is removed from the general surface of Britain every year. One foot will be planed away in 8800 years. If the mean height of the British Islands be taken at 650 feet, then, if the ratio now assumed were to continue, these islands might be levelled in about five and a half millions of years. Much

more detailed observation is needed before any estimate of this kind can be based upon accurate and reliable data. But it illustrates a method of vividly bringing before the mind the reality and extent of the denudation now in progress.

2. *Subaerial denudation—the unequal erosion of land.*

It is obvious that the earthy matter annually removed from the surface of the land does not come equally from the whole surface. The determination of its total quantity furnishes no aid in apportioning the loss, or in ascertaining how much each part of the surface has contributed to the total amount of sediment. On plains, watersheds, and more or less level ground, the proportion of loss may be small, while on slopes and in valleys it may be great, and it may not be easy to fix the true ratios in these cases. But it must be borne in mind that estimates and measurements of the sum-total of denudation are not thereby affected. If we allow too little for the loss from the surface of the tablelands, we increase the proportion of the loss sustained by the sides and bottoms of the valleys, and *vice versâ*.

While these proportions vary indefinitely with the form of the surface, rainfall, &c., the balance of loss must always be, on the whole, on the side of the sloping surfaces. In order to show the full import of this part of the subject, certain ratios may here be assumed which are probably understatements rather than exaggerations. Let us take the proportion between the extent of the plains and tablelands of a country, and the area of its valleys, to be as nine to one; in other words, that of the whole surface of the country, nine-tenths consists of broad undulating plains, or other comparatively level ground, and one-tenth of steeper slopes. Let it be further assumed that the erosion of the surface is nine times greater over the latter than over the former area, so that while the more level parts of the country have been lowered one foot, the valleys have lost nine feet. If, following the measurements and calculations already given, we admit that the mean annual quantity of detritus carried to the sea may, with some probability, be regarded as equal to the yearly loss of $\frac{1}{6000}$ of a foot of rock from the general surface of the country, then, apportioning this loss over the surface in the ratio just given, we find that it amounts to $\frac{5}{9}$ of a foot from the more level grounds in 6000 years, and 5 feet from the valleys in the same space of time. Now, if $\frac{5}{9}$ of a foot be removed from the level grounds in 6000 years, 1 foot will be removed in 10,800 years; and if 5 feet be worn out of the valleys in 6000 years, 1 foot will be worn out in 1200 years. This is equal to a loss of only $\frac{1}{12}$ of an inch from the tableland in 75 years, while the same amount is excavated from the valleys in $8\frac{1}{3}$ years.

It may seem at first sight that such a loss as only a single line from the surface of the open country during more than the lapse of a long human life is almost too trifling to be taken into account, as

it is certainly too small to be generally appreciable. In the same way, if we are told that the constant wear and tear which is going on before our eyes in valleys and watercourses, does not effect more than the removal of one line of rock in eight and a half years, we may naturally enough regard such a statement as probably an underestimate. But if we only permit the multiplying power of time to come into play, the full force of these seemingly insignificant quantities is soon made apparent. For we find by a simple piece of arithmetic, that at the rate of denudation which has been just postulated as probably a fair average, a valley 1000 feet deep may be excavated in 1,200,000, a period which, in the eyes of most geologists, will seem short indeed.

Objection may be taken to the ratios from which this average rate of denudation is computed. Without attempting to decide what this average rate actually is—a question which must be determined for each region upon much fuller data than are at present available—the geologist will find advantage in considering, from the point of view now indicated, what, according to the most probable estimates, is actually in progress around him. Let him assume any other apportioning of the total amount of denudation, he does not thereby lessen the measurement of that amount, which can be and has been ascertained in the annual discharge of rivers. A certain determined quantity of rock is annually worn off the surface of the land. If, as already remarked, we represent too large a proportion to be derived from the valleys and watercourses we diminish the loss from the open country; or, if we make the contingent derived from the latter too great we lessen that from the former. Under any ascertained or assumed proportion the facts remain, that the land loses a certain ascertainable fraction of a foot from its general surface per annum, and that the loss from the valleys and watercourses is larger than that fraction, while the loss from the level grounds is less.

3. *Marine denudation—its comparative rate.*

From the destructive effects of occasional storms an exaggerated estimate has been formed of the relative potency of marine erosion. That the amount of waste by the sea must be inconceivably less than that effected by the subaerial agents will be evident if we consider how small is the extent of surface exposed to the power of the waves when contrasted with that which is under the influence of atmospheric waste. In the general degradation of the land this is an advantage in favour of the subaerial agents, which would not be counterbalanced unless the rate of waste by the sea were many thousands or millions of times greater than that of rains, frosts, and streams. But in reality no such compensation exists. In order to see this, it is only necessary to place side by side measurements of the amount of work actually performed by the two classes of agents. Let us suppose, for instance, that the sea eats away a continent at the rate of ten feet in a century—an estimate which probably attributes to the waves a

much higher rate of erosion than can, as the average, be claimed for them.[1] Then a slice of about a mile in breadth will require about 52,800 years for its demolition, ten miles will be eaten away in 528,000 years, one hundred miles in 5,280,000 years. Now we have already seen that, on a moderate computation, the land loses about a foot from its general surface in 6000 years, and that by the continuance of this rate of subaerial denudation, the continent of Europe might be worn away in about 4,000,000 years. Hence, before the sea, advancing at the rate of ten feet in a century, could pare off more than a mere marginal strip of land, between 70 and 80 miles in breadth, the whole land might be washed into the ocean by atmospheric denudation.

Some such results as these would necessarily be produced if no disturbance took place in the relative levels of sea and land. But in estimating the amount of influence to be attributed to each of the denuding agents in past times, we require to take into account the complicated effects which would arise from the upheaval or depression of the earth's crust. If frequent risings of the land or elevations of the sea-floor into land had not taken place in the geological past, there could have been no great thickness of stratified rocks formed, for the first continents must soon have been washed away. But the great depth of the stratified part of the earth's crust and the abundant breaks and unconformabilities among these sedimentary masses, show how constantly on the one hand the waste of the land was compensated by the result of elevatory movements, while on the other, the continued upward growth of vast masses of sedimentary deposits was rendered possible by prolonged depression of the sea-bed.

When a mass of land is raised to a higher level above the sea, a larger surface is exposed to denudation. As a rule a greater rainfall is the result, and consequently also a more active waste of the surface by subaerial agents. It is true that a greater extent of coast line is exposed to the action of the waves, but a little reflection will show that this increase will not, on the whole, bring with it a proportionate increase in the amount of marine denudation. For as the land rises the cliffs are removed from the reach of the breakers, and a more sloping beach is produced on which the sea cannot act with the same potency as when it beats against a cliff-line. Moreover, as the sea-floor approaches nearer to the surface of the water it is the former detritus washed off the land and deposited under the sea, which first comes within the reach of the currents and waves. This serves, in some measure, as a protection to the solid rock below, and must be cut away by the ocean before that rock can be exposed anew. While, therefore, elevatory movements tend on the whole to accelerate the action of subaerial denudation, they in some degree check the

[1] It may be objected that this rate is far below that of parts of the east coast of England, where the land sometimes loses three or four yards in one year. But on the other hand, along the rocky western coast, the loss is perhaps not so much as one foot in a century.

natural and ordinary influence of the sea in wasting the land. Again, the influence of movements of depression will probably be found to tend in an opposite direction. The lowering of the general level of the land will, as a rule, help to lessen the rainfall, and consequently the rate of subaerial denudation. At the same time it will aid the action of the waves by removing under their level the detritus produced by them and heaped up on the beach, and by thus bringing constantly within reach of the sea fresh portions of the land-surface. But even with these advantages in favour of marine denudation, the balance of power will probably, on the whole, remain always on the side of the subaerial agents.

4. *Marine Denudation—its final result.*

The general result of the erosive action of the sea on the land is the production of a submarine plain. As the sea advances the sites of successive lines of beach pass under low-water mark. Where erosion is in full operation the littoral belt, as far down as wave-action has influence, is ground down by moving detritus (Fig. 162). This result may often be instructively observed, on a small scale, upon rocky shores where sections like that in Fig. 165 occur. We can conceive that should no change of level between sea and land take place, the sea might slowly eat its way far into the land, and produce a gently sloping yet apparently almost horizontal selvage of plain

FIG. 168.—ROCKS GROUND DOWN TO A PLAIN ON THE BEACH BY WAVE-ACTION.

covered permanently by the waves. In such a submarine plain the influence of geological structure, and notably of the relative powers of resistance of different rocks, would make itself conspicuous, as may be seen even on a small scale on any rocky beach (Fig. 168). The present promontories caused by the superior hardness of their component rocks would no doubt be represented by ridges on the subaqueous plateau, while the existing bays and creeks worn out of softer rocks would be marked by lines of valleys or hollows.[1]

This tendency to the formation of a submarine plain along the margin of the land deserves special attention by the student of denudation. The angle at which a mass of land descends to the sea-level serves roughly to indicate the depth of water near shore. A precipitous coast commonly rises out of deep water; a low coast is usually skirted with shallow water, the line of slope above sea-level

[1] Mr. Whitaker, in the excellent paper on subaerial denudation cited on p. 433, has pointed out the different results which are obtained by the subaerial forces from those of sea-action in the production of lines of cliff.

being in a general way prolonged below it. The belt of beach forms a kind of terrace or notch along the maritime slope. Sometimes, where the coast-line is precipitous, this terrace is nearly or wholly wanting. In other places it runs out a good way beyond low-water mark. On a great scale the floor of the North Sea and that

Fig. 169.—Map of British Submarine Platform.

The darker tint represents sea-bottom more than 100 fathoms deep, while the paler shading shows the area of less depths. The figures mark the depth in fathoms. The narrow channel between Norway and Denmark is 2580 feet deep.

of the Atlantic Ocean, for a distance of 300 miles to the west of Ireland, may be regarded as a marine platform that once formed part of the European continent (Fig. 169), and has been reduced by denudation and subsidence to its present position.

So far as the present *régime* of nature has been explored, it would seem to be inevitable that, unless where subterranean movements interfere, or where volcanic rocks are poured forth at

the surface, a submarine plain should be formed along the margin of the land. This final result of denudation has been achieved again and again in the geological past, as is shown by the existence of tablelands of erosion (*ante*, p. 40). To these tablelands the name of "plains of marine denudation" has been applied by A. C. Ramsay. From what has now been said, however, it will be seen that in their actual production the sea has really had less to do than the meteoric agents. A "plain of marine denudation" is that sea-level to which a mass of land has been reduced mainly by the subaerial forces; the line below which further degradation became impossible, because the land was thereafter protected by being covered by the sea. Undoubtedly the last touches in the long process of sculpturing were given by marine waves and currents, and the surface of the plain, save where it has subsided, may correspond generally with the lower limit of wave-action. Nevertheless, in the past history of our planet the influence of the ocean has probably been far more conservative than destructive. Beneath the reach of the waves the surface of the abraded land has escaped the demolition which sooner or later overtakes all that rises above them.

5. *Deposition—the framework of new land.*

If a survey of the geological changes in daily progress upon the surface of the earth leads us to realise how momentously the land is being worn down by the various epigene agents, it ought also to impress us with the vast scale on which new formations—the foundation of future land—are being continually accumulated. Every foot of rock removed from the surface of a country is represented by a corresponding amount of sedimentary material arranged somewhere beneath the sea. Denudation and deposition are synchronous and co-equal.

On land vast accumulations of detrital formations are now in progress. Alluvial plains of every size, from those of mere brooks up to those of the largest rivers, are built up of gravel, sand, and mud derived from the disintegration of higher ground. From the level of the present streams successive terraces of these formations can be followed up to heights of several hundred feet. Over wide regions the daily changes of temperature and wind supply a continual dust, which, in the course of centuries, has accumulated to a depth of sometimes 1500 feet, and covers thousands of square miles of the surface of the continents. The numerous lakes that dot the surface of the land serve as receptacles in which a ceaseless deposition of sediment takes place. Already an unknown number of once existent lakes has been entirely filled up with detrital accumulations, and every stage towards extinction may be traced in those that remain.

But extensive though the terrestrial sedimentary deposits may be, they can be regarded merely as temporary accumulations of the

detritus. Save where protected and concealed under the water of lakes, they are everywhere exposed to a renewal of the denudation to which they owe their origin. Only where the sediment is strewn over the sea-floor beneath the limit of breaker-action is it permitted to accumulate undisturbed. In these quiet depths are now growing the shales, sandstones, and limestones, which by future terrestrial revolutions will be raised into land, as those of older times have been. Between the modern deposits, and those of former sea bottoms which have been upheaved, there is the closest parallel. Deposition will obviously continue as long as denudation lasts. The secular movements of the crust seem to have been always sufficiently frequent and extensive to prevent cessation of these operations. And so we may anticipate that it will be for many geological ages yet to come. Elevation of land will repair what has been lost by superficial waste, and subsidence of sea-level will provide space for continued growth of sedimentary deposits.

Section III.—Life.

Among the agents by which geological changes are now, and in past time have been effected upon the earth's surface living organisms take by no means an unimportant place. They serve as a vehicle for continual transferences from the atmosphere into the mineral world, and from the mineral world back into the atmosphere. Thus they decompose atmospheric carbon dioxide, and in this process have gradually removed from the atmosphere the vast volumes of this gas now locked up within the earth's crust in beds of solid coal. By their decomposition organic acids are produced which partly enter into mineral combinations, and partly return to the atmosphere as carbon dioxide. Plants abstract from the soil silica, alkalies, calcium phosphate and other mineral substances which enter largely into the composition of the hard parts of animals. On the death and decomposition of animals these substances are once more relegated to the inorganic world, thence to enter upon a new circulation through the tissues of living organisms.

From a geological point of view the operations of organic life may be considered under three aspects—destructive, conservative, and reproductive.

§ 1. Destructive Action.

Plants in several ways promote the disintegration of rocks.

1. By keeping the surfaces of rocks moist, they provide means for the continuous solvent action of water. This influence is particularly observable among liverworts, mosses and similar moisture-loving plants.

2. By their decay they supply an important series of organic acids which exert a powerful influence upon soils, minerals and rocks. The

humus, or organic portion of vegetable soil, consists of the remains of plants and animals in all stages of decay, and contains a complex series of organic compounds still imperfectly understood. Among these are humic, crenic and apocrenic acids. The action of these organic acids is twofold. (1.) From their tendency to oxidation they exert a markedly reducing influence (*ante* p. 332). Thus they convert metallic sulphates into sulphides, as in the abundant pyritous incrustations of coal-seams, shell-bearing clays, and even sometimes of mine timbers. Metallic salts are still further reduced to the state of native metals. Native silver occurs among silver ores in fossil wood among the Permian rocks of Hesse. Native copper has been frequently noticed in the timber props of mines; it was found hanging in stalactites from the timbers of the Ducktown copper mines, Tennessee, when the mines were re-opened after being shut up during the civil war. Fossil fishes from the Kupferschiefer have been encrusted with native copper, and fish teeth have been obtained from Liguria completely replaced by this metal. (2.) They exert a remarkable power of dissolving mineral substances. This phase of their activity has probably been undervalued by geologists.[1] Experiments have shown that many of the common minerals of rocks are attacked by organic acids. There is reason to believe that in the decomposition effected by meteoric waters, and usually attributed mainly to the operation of carbonic acid, the initial stages of attack are due to the powerful solvent capacities of the humus acids. Owing, however, to the facility with which these acids pass into higher states of oxidation, it is chiefly as carbonates that the results of their action are carried down into deeper parts of the crust or brought up to the surface. Carbonic acid is no doubt the final condition into which these unstable organic compounds pass. During their existence, however, they attack not merely alkalies and alkaline earths, but even dissolve silica. The relative proportion of silica in river waters has been referred to the greater or less abundance of humus in their hydrographical basins,[2] the presence of a large percentage of silica being a concomitant of a large proportion of organic matter. Further evidence of the important influence of organic acids upon the solution of silica is supplied by many siliceous deposits (p. 463).

Wherever a layer of humus has spread over the surface of the land, traces of its characteristic decompositions may be found in the soils, subsoils and underlying rocks. Next the surface the normal colour of the subsoils is usually changed by oxidation and hydration into tints of brown and yellow, the lower limit of the weathered zone being often sharply defined. It has recently been proposed to ascribe mainly to the operation of the humus acids the thick layer of decomposed rock above (p. 338) noticed as observable so frequently

[1] This has recently been strongly insisted upon by A. A. Julien in a memoir on the Geological Action of the Humus Acids. *Amer. Assoc.* 1879, p. 311.
[2] Sterry Hunt's "Chemical and Geological Essays," pp. 126, 150.

south of the limits of the ice of the glacial period, and the inference has been drawn that even where the surface is now comparatively barren the mere existence of this thick decomposed layer affords a presumption that it once underlay an abundant vegetation, such as a heavy primeval forest-growth.[1] Nor is the chemical action confined to the superficial layers. The organic acids are carried down beneath the surface, and initiate that series of alterations which carbonic acid and the alkaline carbonates effect among subterranean rock-masses (*ante* p. 348).

3. Plants insert their roots or branches between the joints of rock or penetrate beneath the soil. Two marked effects are traceable to this action. In the first place large slices of rock may be wedged off from the sides of wooded hills and cliffs. Even among old ruins an occasional sapling ash or elm may be found to have cast its roots round a portion of the masonry and to be slowly detaching it from the rest of the wall. In the second place the soil and subsoil are opened up to the decomposing influences of the air and descending water. The distances to which, under favourable circumstances, roots may penetrate downward are much greater than might be supposed. Thus in the loess of Nebraska the buffalo-berry (*Shepherdia argophylla*) has been observed to send a root 55 feet down from the surface, and in that of Iowa the roots of grasses penetrate from 5 to 25 feet.[2]

4. By attracting rain, as thick forests, woods and mosses, more particularly on elevated ground, are believed to do, plants accelerate the general scouring of a country by running water. The indiscriminate destruction of the woods in the Levant has been assigned, with much plausibility, as the main cause of the present desiccation of that region.[3]

5. Plants promote the decay of diseased and dead plants and animals, as when fungi overspread a damp rotting tree or the carcase of a dead animal.

Animals.—The destructive influences of the animal kingdom likewise show themselves in several distinct ways.

1. The surface soil is moved, and exposed thereby to attack by rain, wind, &c. As Darwin showed, the common earth-worm is continually engaged in bringing up the fine particles of soil to the surface. He found that in fifteen years a layer of burnt marl had been buried under 3 inches of loam which he attributed to this operation.[4] It has been already pointed out that part of the growth of soil may be due to wind-action (*ante* p. 321). There can be no doubt, however, that the materials of vegetable soil are largely commingled and fertilized by the earth-worm, and in particular that, by being brought

[1] Julien, *op. cit.* p. 378.

[2] Aughey's "Physical Geography and Geology of Nebraska," 1880, p. 275.

[3] See on this disputed question the works cited by Rolleston, *Journ. Roy. Geog. Soc.* xlix. (1879). The destruction of forests is also alleged to increase the number and severity of hail-storms.

[4] *Trans. Geol. Soc.* v. p. 505.

up to the surface, the fine particles are exposed to meteoric influences; notably to wind and rain. Even a grass-covered surface may, from this cause, suffer a slow denudation.

Burrowing animals, by throwing up the soil and subsoil, expose these to be dried and blown away by the wind. At the same time their subterranean passages serve to drain off the superficial water and to injure the stability of the surface of the ground above them. In Britain the mole and rabbit are familiar examples. In North America the prairie dog and gopher have undermined extensive tracts of pasture land in the west. In Cape Colony wide areas of open country seem to be in a constant state of eruption from the burrowing operations of multitudes of *Bathyergi* and *Chrysochloris*—small mole-like animals which bring up the soil and bury the grassy vegetation under it. The decomposition of animal remains gives rise to some of the same chemical changes as are produced by that of plants.

2. The flow of streams is sometimes interfered with, or even diverted, by the operations of animals. Thus the beaver, by cutting down trees (sometimes one foot or more in diameter) and constructing dams with the stems and branches, checks the flow of watercourses, intercepts floating materials, and sometimes even diverts the water into new channels. This action is typically displayed in Canada and in the Rocky Mountain regions of the United States. Thousands of acres in many valleys have been converted into lakes, which, intercepting the sediment carried down by the streams, and being likewise invaded by marshy vegetation, have subsequently become morass and finally meadow-land. The extent to which, in these regions, the alluvial formations of valleys have been modified and extended by the operations of the beaver is almost incredible. The embankments of the Mississippi are sometimes weakened to such an extent by the burrowings of the cray-fish as to give way and

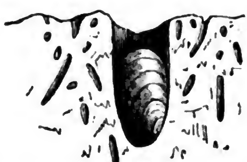


FIG. 170.—SHELL-BORINGS IN LIMESTONE.

allow the river to inundate the surrounding country. Similar results have happened in Europe from the subterranean operations of rats.

3. Some Mollusca (*Pholas, Saxicava, Teredo,* &c., Fig. 170) bore into stone or wood, and by the number of contiguous perforations greatly weaken the material. Pieces of drift-wood are soon riddled

with long holes by the teredo; while wooden piers, and the bottoms of wooden ships, are often rapidly perforated. Saxicavous shells, by piercing stone and leaving open cavities for rain and sea-water to fill, promote its decay.

4. Many animals exercise a ruinously destructive influence upon vegetation. Of the various insect plagues of this kind it will be enough to enumerate the locust, phylloxera, and Colorado beetle. The pasture in some parts of the south of Scotland has in recent years been much damaged by mice, which have increased in numbers owing to the indiscriminate shooting and trapping of owls, hawks, and other predaceous creatures. Grasshoppers cause the destruction of vegetation in some parts of Wyoming and other Western Territories of the United States. The way in which animals destroy each other, often on a great scale, may likewise be included among the geological operations now under description.

§ 2. Conservative Action.

Plants.—The protective influence of vegetation is well known. 1. The formation of a stratum of turf protects soil and rocks from being rapidly removed by rain or wind. Hence the surface of a district so protected is denuded with extreme slowness except along the lines of its water-courses.

2. Many plants, even without forming a layer of turf, serve by their roots or branches to protect the loose sand or soil on which they grow from being removed by wind. The common sand-carex and other arenaceous plants bind littoral sand-dunes and give them a permanence which would at once be destroyed were the sand laid bare again to storms. In North America the sandy tracts of the Western Territories are in many places protected by the sage-brush and grease-wood. The growth of shrubs and brushwood along the course of a stream not only keeps the alluvial banks from being so easily undermined and removed as would otherwise be the case, but serves to arrest the sediment in floods, filtering the water, and thereby adding to the height of the flood plain. On some parts of the west coast of France extensive ranges of sand-hills have been gradually planted with pine woods, which, while preventing the destructive inland march of the sand, also yield a large revenue in timber, and have so influenced the climate as to make these districts a resort for pulmonary invalids.[1] In tropical countries the mangrove grows along the sea-margin, and not only protects the land, but adds to its breadth, by forming and increasing a maritime alluvial belt.

3. Some marine plants likewise afford protection to shore rocks. This is done by the hard incrustation of calcareous nullipores; like-

[1] De Lavergne, "Economie rurale de la France depuis 1789," p. 297. *Edin. Review*, Oct. 1864, article on Coniferous Trees.

wise by the tangles and smaller fuci which, growing abundantly on the littoral zone, break the force of waves, or diminish the effects of ground swell.

4. Forests and brushwood protect soil, especially on slopes, from being washed away by rain. This is shown by the disastrous results of the thoughtless destruction of woods. According to Reclus,[1] in the three centuries from 1471 to 1776, the "vigueries," or provostry-districts of the French Alps, lost a third, a half, and even three-fourths of their cultivated ground, and the population has diminished in somewhat similar proportions. From 1836 to 1866 the departments of Hautes and Basses Alpes lost 25,000 inhabitants, or nearly one-tenth of their population—a diminution which has with plausibility been assigned to the reckless removal of the pine forests, whereby the steep mountain sides have been washed bare of their soil. The desiccation of the countries bordering the eastern Mediterranean has been ascribed to a similar cause.[2]

5. In mountain districts pine forests exercise also an important conservative function in preventing the formation or arresting the progress of avalanches. In Switzerland some of the forests which cross the lines of frequent snow-falls are carefully preserved.

Animals do not exert any important conservative action upon the earth's surface, save in so far as they form new deposits, as will be immediately referred to. In the prairie regions of Wyoming and other tracts of North America, some interesting minor effects are referable to the herds of roving animals which migrate over these territories. The trails made by the bison, the elk, and the big-horn or mountain-sheep are firmly trodden tracks on which vegetation will not grow for many years. All over the region traversed by the bison numerous circular patches of grass are to be seen which have been formed on the hollows where this animal has wallowed. Originally they are shallow depressions formed in great numbers where a herd of bisons has rested for a time. On the advent of the rains they become pools of water; thereafter grasses spring up luxuriantly, and so bind the soil together that these grassy patches, or "bison-wallows," may actually become slightly raised above the general level if the surrounding ground becomes parched and degraded by winds.[3]

§. 3. Reproductive Action.

Plants.—Both plants and animals contribute materials towards new geological formations, chiefly by the aggregation of their remains, partly from their chemical action. Their remains are enclosed in deposits of sand and mud, the bulk of which they thus help to

[1] *La Terre*, p. 410.

[2] Recent attempts to reclothe the dessicated stone-wastes of Dalmatia with trees have been attended with success. See Mojsisovics, *Jahrb. Geol. Reichsanst.* 1880, p. 210.

[3] Comstock in Captain Jones' "Reconnaissance of N.W. Wyoming," 1875, p. 175.

increase, and likewise by themselves form not unimportant deposits. Of plant formations the following illustrative examples may be given:—

1. Humus, Black Soils, &c.—Long continued growth and decay of vegetation upon a land surface, not only promotes disintegration of the superficial rock, but produces an organic residue, the intermingling of which with mineral débris constitutes vegetable soil. Undisturbed through long ages, this process has, under favourable conditions, given rise to thick accumulations of a rich dark loam. Such are the "regur," or rich black cotton soil of India, the "tchernayzem," or black earth, of Russia, containing from 6 to 10 per cent. of organic matter, and the deep fertile soil of the American prairies and savannahs. These formations cover plains many thousands of square miles in extent. The "tundras" of northern latitudes are frozen plains of which the surface is covered with arctic mosses and other plants.[1]

2. Peat-mosses and Bogs.—In temperate and arctic latitudes, marshy vegetation accumulates in places to a depth of sometimes 40 or 50 feet in what are termed bogs or peat-mosses. In northern Europe and America these vegetable deposits have been largely formed by mosses, especially species of *sphagnum*, which, growing on hill tops, slopes, and valley bottoms as a wet spongy fibrous mass, die in their lower parts and send out new fibres above. Among the Alps, as also in the northern parts of South America, and among the Chatham Islands, east of New Zealand, the same part is played by various phanerogamous plants, which form on the surface a thick stratum of peat. A succession can sometimes be detected in the vegetation out of which the peat has been formed. Thus in Europe among the bottom layers traces of rush (*Juncus*), sedge (*Iris*), and fescue-grass (*Festuca*) may be observed, while not infrequently an underlying layer of fresh-water marl, full of mouldering shells of *Limnea*, *Planorbis* and other lacustrine molluscs, shows that the area was originally a lake which has been filled up with vegetation. The next and chief layer of the peat will usually be found to consist mainly of matted fibres of different mosses, particularly *Sphagnum*, *Polytrichum*, and *Bryum*, mingled with roots of coarse grasses and aquatic plants. The higher layers frequently abound in the remains of heaths. Every stage in the formation of peat may be observed in the section cut in mosses for fuel: the portions at the bottom being more or less compact dark brown or black, with comparatively little external appearance of vegetable structure, while those at the top are loose, spongy, and fibrous, where the living and dead parts of the mosses commingle (Fig. 171).

It frequently happens that remains of trees occur in peat-mosses.

[1] It may be well to take note here again of the extensive accumulation of red loam in limestone regions which have long been exposed to atmospheric influences. To what extent vegetation may co-operate in the production of this loam has not been determined. Fuchs believes that the "terra rossa" is only present in dry climates where the amount of humus is small. (*Ante*, p. 338, and authorities there cited.)

Sometimes the roots are imbedded in soil underlying the moss, showing that the moss has formed since the growth of the trees.

FIG. 171.—VIEW OF SCOTTISH PEAT-MOSS OPENED FOR DIGGING FUEL.

In other cases the roots and trunks occur in the heart of the peat, proving that the trees grew upon the mossy surface, and were finally, on their decay, enclosed in growing peat (Fig. 172). A succession of trees has been observed among the Danish peat-mosses, the Scotch fir (*Pinus sylvestris*) and white birch (*Betula alba*) being characteristic of the lower layers; higher portions of the peat being marked by remains

FIG. 172.—SCENE IN A SUTHERLANDSHIRE PEAT-MOSS.

of the oak, while at the top comes the common beech. Remains of trees are abundant in the bogs of Scotland and Ireland.

The rate of growth of peat varies within wide limits. An interesting example of the formation and growth of peat-moss in the latter half of the seventeenth century is on record.[1] In the year 1651 an ancient pine forest occupied a level tract of land among the hills in the west of Ross-shire. The trees were all dead, and in a condition to be blown down by the wind. About fifteen years later every vestige of a tree had disappeared, the site being occupied by a spongy green bog into which a man would sink up to the arm-pits. Before the year 1699 it had become firm enough to yield good peat for fuel. In a moor in Hanover a layer of peat from 4 to 6 feet thick formed in about thirty years. Near the Lake of Constance a layer of 3 to 4 feet grew in 24 years. Among the Danish mosses a period of 250 to 300 years has been required to form a layer 10 feet thick. Much must depend upon the climate, slope, drainage and soil. Some European peat-mosses are probably of extreme antiquity, having begun to form soon after the surface was freed from the snow and ice of the glacial period. In the lower parts of these mosses traces of the arctic flora which then overspread so much of the continent are to be met with. Change of climate and likewise of drainage may stop the formation of peat, so that shrubs and trees spring up on the firm surface.

Peat-mosses cover many thousand square miles of Europe and North America. About one-seventh of Ireland is covered with bogs, that of Allen alone comprising 238,500 acres, with an average depth of 25 feet. Where lakes are gradually converted into bogs, the marshy vegetation advances from the shores, and sometimes forms a matted treacherous green surface, beneath which the waters of the lake still lie. The decayed vegetable matter from the under part of this crust sinks to the bottom of the water, forming there a fine peaty mud, which slowly grows upward. Eventually, as the spongy covering spreads over the lake, a layer of brown muddy water may be left between the still growing vegetation above and the muddy deposit at the bottom. Heavy rains, by augmenting this intermediate watery layer, sometimes make the centre swell up until the matted skin of moss bursts, and a deluge of black mud pours into the surrounding country. Many disastrous examples of this kind have been witnessed in Ireland and Scotland. The inundated ground is covered permanently with a layer of black peaty earth.

From the treacherous nature of their surface peat-mosses have frequently been the receptacles for bodies of men and animals that ventured upon them. As peat possesses great antiseptic power, these remains are usually in a state of excellent preservation. In Ireland the remains of the extinct large Irish elk (*Megaceros Hibernicus*) have been dug up from many of the bogs. Human weapons, tools and ornaments have been recovered abundantly from peat-mosses; likewise crannoges, or pile dwellings (constructed in the original

[1] Earl of Cromarty, *Phil. Trans.* xxvii.

lakes that preceded the mosses), and canoes hollowed out of single trees.[1]

3. Mangrove Swamps.—On the low moist shores and river mouths of tropical countries, the mangrove tree plays an important geological part. It grows in such situations in a dense jungle, sometimes twenty miles broad, which fringes the coast as a green selvage, and runs up, if it does not quite occupy, creeks and inlets. The mangrove flourishes in sea-water even down to low-water mark, forming there a dense thicket, which, as the trees drop their radicles and take root, grows outward into the sea. It is singular to find terrestrial birds nestling in the branches above and crabs and barnacles living among the roots below. By this network of subaqueous radicles and roots the water is filtered of its sediment, which, retained among the vegetation, helps to turn the spongy jungle into a firm soil. On the coast of Florida the mangrove swamps stretch for long distances as a belt from five to twenty miles broad, which winds round the creeks and inlets. At Bermuda the mangroves co-operate with grasses and other plants to choke up the creeks and brackish lakes. In these waters calcareous algæ abound, and, as their remains are thrown up amidst the sand and vegetation, they form a remarkably calcareous soil.[2]

4. Diatom Earth or Ooze.—As the minute siliceous plants called diatoms occur both in fresh and salt water, the deposit formed from their congregated remains is found both on the sites of lakes and on the sea-floor. "Infusorial" earth and "tripoli powder" consist mainly of the frustules and fragmentary débris of diatoms which have accumulated on the bottoms of lacustrine areas. The purer varieties contain 90 to 97 per cent. of silica. They form beds sometimes upwards of thirty feet thick. (Richmond in Virginia and Bilin in Bohemia.) Towards the Antarctic circle the *Challenger* met with *Diatomaceæ* in abundance, both in the surface waters of the ocean and on the bottom. They form at depths of from 1260 to 1975 fathoms a pale straw-coloured deposit, which when dried is white and very light (Fig. 173).

5. Chemical Deposits.—But, besides giving rise to new formations by the mere accumulation of their remains, plants do so also both directly and indirectly by originating or precipitating chemical solutions. The most conspicuous example of this action is the production of calc-sinter. Some plants (several species of *Chara*, for instance) have the power of decomposing the carbonic acid dissolved in water, and precipitating calcium carbonate within their own cell walls. Others (such as the mosses *Hypnum*, *Bryum*, *&c.*[3])

[1] On the composition, structure, and history of peat-mosses, consult Rennie's "Essays on Peat-moss," Edinburgh, 1810. Templeton, *Trans. Geol. Soc.* v. p. 608. Pokorny, *Verhand. Geol. Reichsanst. Vienna*, 1860; Senft, "Humus-, Marsch-, Torf- und Limonit-bildungen," Leipzig, 1862; J. Geikie, *Trans. Roy. Soc. Edin.* xxiv. p. 363. For a full list of plants that supply vegetable material for the formation of peat, see T. Rupert Jones, *Proc. Geologist's Association*, 1880, p. 217.

[2] See Nelson, *Q. J. Geol. Soc.* ix. p. 200, *et seq.*

[3] Also phanerogams, as *Ranunculus* and *Potamogeton*.

precipitate the carbonate as an inorganic incrustation outside their own substance. Some observers have even maintained that this is

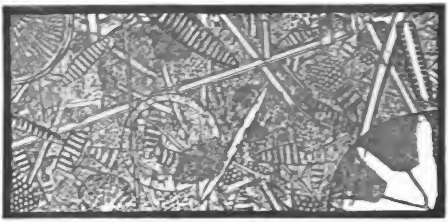


Fig. 173.—Diatom-ooze dredged up by the *Challenger* Expedition from a Depth of 1950 Fathoms in the Antarctic Ocean. Lat. 53° 85 S.; Long. 108° 38 E. Magnified 300 Diameters.

the normal mode of production of calc-sinter, in large masses like those of Tivoli. It is certainly remarkable that this substance may be observed encrusting fibrous bunches of moss (*Hypnum, &c.*) when it can be found in no other part of the water-course, and this, too, at a spring containing only 0·034 of carbonate. It is evident that the deposit of calc-sinter cannot be due to mere evaporation, otherwise it would be more or less equally spread along the edges and shallow parts of the channel. It arises first, from the decomposition of dissolved carbonic acid by the living plants, and it proceeds along their growing stems and fibres. Subsequently evaporation and loss of carbon dioxide cause the carbonate to be precipitated over and through the fibrous sinter till the substance may become a solid crystalline stone. Varieties of sinter are traceable to original differences in the plants precipitating it. Thus at Weissenbrunen, near Schalkau, in central Germany, a cavernous but compact sinter is made by *Hypnum molluscum*, while a loose porous kind gathers upon *Didymodon capillaceus.*[1]

Some marine algæ, as above noticed, abstract calcium carbonate from sea-water and build it up into their own substance. A nullipore (*Lithothamnium nodosum*) has been found to contain about 84 per cent. of calcium carbonate, 5½ of magnesium carbonate, with a little phosphoric acid, alumina, and oxides of iron and manganese.[2] Considerable accumulations of such calcareous algæ take place along some shore lines. Broken up by the waves and thrown ashore with fragmentary shells or other organisms, the calcareous detritus is cemented into solid stone by the solvent action of the carbonic acid of rain or oceanic water.

In the formation of extensive beds of bog iron-ore the agency of

[1] See V. Schauroth, *Z. Deutsch. Geol. Ges.* iii. (1851), p. 137. Cohn, *Neues Jahrb.* 1864, p. 580, gives some interesting information as to the plants by which the sinter is formed, and their work. In Scotland *Hypnum commutatum* is a leading sinter-former.

[2] Gümbel, *Abhandl. Bayerisch. Akad. Wissensch.* xi. 1871.

vegetable life is of prime importance. In marshy flats where stagnant water receives a supply of the organic acids from decomposing plants the salts of iron are attacked and dissolved. Exposure to the air leads to the oxidation of these solutions and the consequent precipitation of the iron in the form of hydrated ferric oxide, which, mixed with similar combinations of manganese, and also with silica, phosphoric acid, lime, alumina and magnesia, constitutes the bog-ore so abundant on the lowlands of North Germany and other marshy tracts of northern Europe.[1] On the eastern sea-board of the United States large tracts of salt marsh, lying behind sand-dunes and bars, form receptacles for much active chemical solution and deposit. There, as in the European bog-iron districts, ferruginous sands and rocks containing iron are bleached by the solvent action of humus acids, and the iron removed in solution is chiefly oxidized and thrown down on the bottom. In presence of the sulphates of the sea-water and of organic matter, the iron is there partially reduced into sulphide.[2] The existence of beds of iron-ore among geological formations affords strong presumption of the existence of contemporaneous organic life by which the iron was dissolved and precipitated.

The humus acids, which possess the power of dissolving silica, precipitate it in incrustations and concretions. Julien describes hyalite crusts at the Palisades of the Hudson,[2] due as he thinks, to the action of the rich humus upon the fallen débris of diabase. The frequent occurrence of nodules of flint and chert in association with organic remains, the common silicification of fossil wood, and similar close relations between silica and organic remains, point to the action of organic acids in the precipitation of this mineral. This action may consist sometimes in the neutralization, by organic acids, of alkaline solutions charged with silica;[3] sometimes in the solution and redeposit of colloid silica by albuminoid compounds, developed during the decomposition of organic matter in deposits through which silica has been disseminated, the deposit taking place preferentially round some decaying organism or in the hollow left by its removal.[4]

Animals.—Animal formations are chiefly composed of the remains of the lower grades of the animal kingdom, especially of *Mollusca, Actinozoa, and Foraminifera.*

(1.) Calcareous.—Lime, chiefly in the form of carbonate, is the mineral substance of which the solid parts of invertebrate animals are mainly built up. Hence the great majority of the accumulations formed of animal remains are calcareous. In fresh water they are represented by the *marl* of lakes—a white, chalky deposit consisting of the mouldering remains of *Mollusca, Entomostraca,* and partly of fresh-water algæ. On the sea-bottom, in shallow water, they consist of beds of shells, as in oyster-banks. Here and

[1] Forchhammer, *Neues Jahrb.* 1841, p. 17.
[2] Julien, *Amer. Assoc.* 1879, p. 347.
[3] Leconte, *Amer. Journ. Sci.* 1880, p. 181.
[4] Julien, *op. cit.* 396. Sollas, *Ann. Mag. Nat. Hist.* Nov. Dec. 1880.

there considerable beds of broken shells have been produced by the accumulation of the excrement of fishes, as Verrill has pointed out on the north-eastern coasts of the United States.

Coral-reefs.[1]—But the most striking calcareous formations now in progress are the reefs and islands of coral. These vast masses of rock are formed by the continuous growth of various genera and species of corals, in tracts where the mean temperature is not lower than 68° Fahr. Coral-growth is prevented by colder water, and is likewise checked by the fresh and muddy water discharged into the sea by large rivers. Hence many coast-lines in tropical seas are destitute of coral-reefs.

Darwin and Dana have shown that reef-building corals cannot live at depths of more than about fifteen or twenty fathoms. When they begin to grow, either fronting a coast-line or on a submarine bank, coral reefs continue to advance outward, the living portion being at the surface, while the mass underneath consists of a calcareous skeleton which becomes a solid white compact limestone. In the coral area of the Pacific there are, according to Dana, 290 coral islands, besides extensive reefs round other islands. The Indian Ocean contains some groups of large coral islands. Reefs of coral occur less abundantly in the tropical parts of the Atlantic, among the West Indian Islands and on the Florida coast. The great reef of Australia is 1250 miles long and from 10 to 90 miles broad.

Coral rock, though formed by the continuous growth of the polyps, gradually loses any distinct organic structure, and acquires an internal crystalline character like an ancient limestone, owing to the infiltration of water through its mass, whereby calcium carbonate is carried down and deposited in the pores and crevices as in a growing stalactite. Great quantities of calcareous sand and mud are produced by the breakers which beat upon the outer edge of the reefs. This detritus is partly washed up upon the reefs, where, being cemented by solution and redeposit, it aids in their consolidation, sometimes acquiring an oolitic structure,[2] but in great measure it is swept away by the ocean currents and distributed over many thousands of square miles of the sea-floor.

As already mentioned (p. 282), the formation of coral islands has been explained by Mr. Darwin on the hypothesis of a subsidence of the sea-floor. These circular coral islands, or atolls, rising in mid-ocean, have the general aspect shown in Fig. 174. Their external form may be understood from the chart (Fig. 175), and their structure and the character of their surface from the section (Fig. 176). They rise with sometimes tolerably steep slopes from a depth of 2000 feet and upwards, until they reach the surface of the sea. But as the coral polyps do not live at a greater depth than about 15 or 20 fathoms,

[1] See Darwin, "The Structure and Distribution of Coral Islands," 1842; Dana, "Corals and Coral Islands," 1872; Jukes' "Narrative of Voyage of H.M.S. *Fly*," 1847; Murray, Proc. Roy. Soc. Edin. x. p. 505.

[2] See Dana's "Corals and Coral Islands," pp. 152, 194.

and could not have grown upward therefore from the bottom of a deep sea, Darwin inferred that the sites of these coral reefs had undergone a

FIG. 174.—VIEW OF AN ATOLL, OR CORAL ISLAND.

progressive subsidence, the rate of upward growth of the reefs keeping pace, on the whole, with the depression. In this view what is termed a

FIG. 175.—CHART OF KEELING ATOLL, INDIAN OCEAN (AFTER MR. DARWIN). The white portion represents the reef above sea-level, the inner shaded space the lagoon, of which the deepest portion is marked by the darker tint.

Fringing Reef (A B, Fig. 177) would first be formed fronting the land (L) between the limit of the 20 fathom line and the sea-level (*s s*). Growing upward until it reached the surface of the water, it would be exposed to the dash of the waves, which would break off pieces of the coral and heap them upon the reef. In this way islets

would be formed upon it, which, by successive accumulations of materials thrown up by the breakers or brought by winds, would remain permanently above water. On these islets palms and other plants, whose seeds might be drifted from the adjoining land, would take root and flourish. Inside the reef there would be a shallow channel of water, communicating, through gaps in the reef, with the main ocean outside. Fringing reefs of this character are of common occurrence at the present time. In the case of a continent they front its coast for a long distance, but they may entirely surround an island.

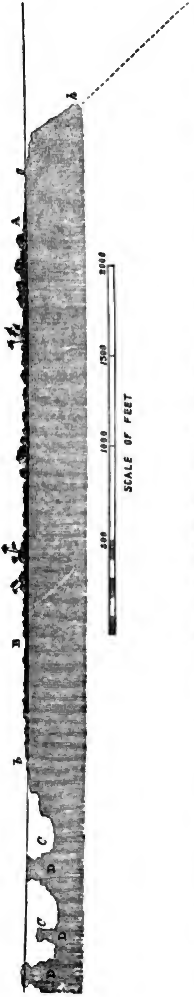


Fig. 176.—Section of a Coral Reef.

A B, Portion above tide mark (*a b*), covered with vegetation and habitable; C C, edge of lagoon, with two insular masses of coral (D D); the open ocean lies to the right of the slope *a h*.

If the site of a fringing reef undergoes depression at a rate sufficiently slow to allow the corals to keep pace with it, the reef may grow upward as fast as the bottom sinks downward. The lagoon channel inside will become deeper and wider, while, at the same time, the depth of water outside will increase until a *Barrier Reef* (A′ B′, Fig. 177) is formed. In Fig. 178, for example, the Gambier Islands (1248 feet high) are shown to be entirely surrounded by an interrupted barrier reef, inside of which lies the lagoon. Prolonged slow depression must continually diminish the area of the land thus encircled, while the reef will retain much the same size and position. At last the final peak of the original island may disappear under the lagoon (C Fig. 177), and an *Atoll*, or true coral island, will be formed (A″ A″ Fig. 177, and Figs. 174 and 175). Should any more rapid or sudden downward movement take place, it might carry the atoll down beneath the surface, as seems to have happened at the Great Chagos bank in the Indian Ocean, which is a submerged atoll.

In this simple and luminous explanation of the history of coral reefs every stage in the progress of the changes is open to observation, from

the incipient fringing reef to the completed and submerged atoll. Every observed fact fits in harmoniously with the others, leading up to the impressive conclusion that a vast area of the Pacific Ocean,

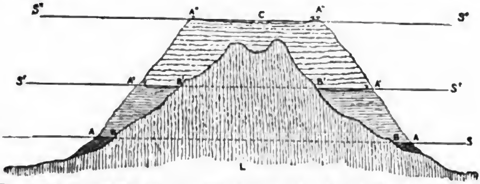


FIG. 177.—DIAGRAM ILLUSTRATING DARWIN'S THEORY OF THE FORMATION OF ATOLLS.

fully 6000 geographical miles from east to west, has undergone a recent subsidence, and may be slowly sinking still.

Mr. Darwin's views having been universally accepted by geologists

FIG. 178.—CHART OF GAMBIER ISLANDS. PACIFIC OCEAN (AFTER BEECHY).

coral islands have been regarded with special interest as furnishing proof of vast oceanic subsidence. Recently, however, Mr. Murray, whose researches in the "*Challenger* Expedition" led him to make

detailed examination of many coral reefs, has offered another explanation of the phenomena. He suggests that barrier reefs do not necessarily prove subsidence, seeing that they may grow outward from the land upon the top of a talus of rock fragments or of their own débris broken down by the waves, and may thus appear to consist of solid coral which had grown upward from the bottom during depression, although only the upper layer, 20 fathoms or thereabouts in thickness, is composed of solid, unbroken coral growth. He points out that in the coral seas the islands appear to have always started on volcanic ejections, at least that all the non-calcareous rock now visible is of volcanic origin. The portion of a volcanic cone (Fig. 179) raised above the sea may be supposed to be cut down

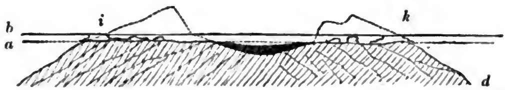


FIG. 179.—SECTION OF A VOLCANIC CONE SUPPOSED TO HAVE BEEN THROWN UP ON THE SEA-FLOOR AND TO HAVE REACHED THE SEA-LEVEL (*B.*).

to the lower limit of breaker action (*a a*), so as to offer a platform on which coral might grow into reefs (*i k*) up to the level of high-water (*b b*). Or, with less denudation, or a loftier cone, a nucleus of the original volcano might remain as an island (Fig. 180), from the sides of which a barrier reef (*r r*) might grow outward, on a talus of its own débris, and maintain a steep outer slope. According to this

FIG. 180.—SECTION OF VOLCANIC ISLAND WITH SURROUNDING CORAL-REEF (*B.*).

view the breadth of a reef ought, in some degree, to be a measure of its antiquity.

To the obvious objection that this explanation requires the existence of so many volcanic peaks just at the proper depth for coral growth, and that the number of true atolls is so great, Mr. Murray replies that in several ways the limit for the commencement of coral growth may be reached. Volcanic islands may be reduced by the waves to mere shoals, like Graham's Island, in the Mediterranean. On the other hand, submarine volcanic peaks, if originally too low, may conceivably be brought up to the coral zone by the constant deposit of the detritus of marine life (foraminifera, radiolaria, pteropods, &c.), which this observer has found to be very abundant in

the upper waters, whence it descends as a kind of organic rain into the depths; though it may be questioned how far such fine sediment would be allowed to accumulate to a sufficient height on account of the scour of the ground-swell (p. 423). Mr. Murray holds also that the dead coral, attacked by the solvent action of the carbonic acid in the sea water, is removed in solution both from the lagoon (which may thus be deepened) and from the dead part of the outer face of the reef, which may in this way acquire greater steepness.[1]

Foraminiferal Ooze.—Recent deep-sea soundings and dredgings have shown that the bed of the Atlantic and other oceans is covered with a remarkable calcareous ooze formed of the remains of *Foraminifera,* and chiefly of species of the genus *Globigerina.* Among abysmal deposits it ranks next in abundance to the red and grey clays of the deep sea (p. 439). It is a pale-grey marl, sometimes red from peroxide of iron, or brown from peroxide of manganese; and it usually contains more or less clay, even with occasional fragments of pumice. It covers an area of the North Atlantic probably not less than 1300 miles from east to west, by several hundred miles from north to south.

(2.) Siliceous deposits formed from animal exuviæ are illustrated by another of the deep-sea formations brought to light by the *Challenger* researches. In certain regions of the western and middle Pacific Ocean, the bottom was found to be covered with an ooze consisting almost entirely of *Radiolaria.* These minute organisms occur, indeed, more or less abundantly in almost all deep oceanic deposits. From the deepest sounding taken by the *Challenger* (4575 fathoms, or more than 5 miles) a radiolarian ooze was obtained (Fig. 181). The spicules of sponges likewise furnish materials towards these siliceous accumulations.

In connection with the organic deposits of the sea-floor, reference may be made here to the chemical processes in progress there, and to the probable part taken in these processes by decaying animal matter. The precipitation of manganic oxide and its segregation in concretions, often round organic centres (p. 440), presents a close analogy to the formation of concretionary bog-iron ore through the operation of the humus acids in stagnant water. The crystallization of silicates in patches, cementing the particles of deep-sea ooze, observed during the *Challenger* expedition, is possibly also to be connected with the action of organic compounds (pp. 441, 463). The formation of flint concretions has been for many years a vexed question in geology. The constant association of flints with traces, more or less marked, of former abundant siliceous organisms seems to make the inference irresistible, that the substance of the flint has been derived from these organisms. The silica has first been abstracted from sea-water by living organisms. It has then been redissolved and redeposited (probably through the agency of decomposing organic matter), sometimes in amorphous concretions,

[1] *Proc. Roy. Soc. Edin.* 1880, p. 505.

sometimes replacing the calcareous parts of echini, molluscs, &c., while the surrounding matrix was, doubtless, still a soft watery ooze under the sea.[1]

(3.) Phosphatic deposits, in the great majority of cases, betoken some of the vertebrate animals, seeing that phosphate of lime enters largely into the composition of their bones and occurs in their excrement (p. 169). The most typical modern accumulations of this nature are the guano beds of rainless islands off the western coasts of South America and Southern Africa. In these regions immense flocks of

Fig. 181.—Radiolarian Ooze.

Dredged up by the *Challenger* expedition, from a depth of 4475 fathoms, in Lat. 11° 24′ N., Long. 143° 10′ E. Magnified 100 diameters. This is from the deepest abyss whence organisms have yet been obtained.

sea-fowl have, in the course of centuries, covered the ground with an accumulation of their droppings to a depth of sometimes 30 to 80 feet, or even more. This deposit, consisting chiefly of organic matter and ammoniacal salts, with about 20 per cent. of phosphate of lime, has acquired a high value as a manure, and is being rapidly cleared off. It could only have been preserved in a rainless or almost rainless climate. In the west of Europe isolated stacks and rocky islands in the sea are often seen to be white from the droppings of clouds of sea-birds; but it is merely a thin crust, which is not allowed to grow thicker in a climate where rains are frequent and heavy.

[1] See Wallace, *Q. J. Geol. Soc.* xxxvi., Sollas, *Ann. & Mag. Nat. Hist.* 5th series, vi. p. 437, and *ante*, p. 463.

§ 4. Man as a Geological Agent.

No survey of the geological workings of plant and animal life upon the surface of the globe can be complete which does not take account of the influence of man—an influence of an enormous and increasing consequence in physical geography; for man has introduced, as it were, an element of antagonism to nature. Not content with gathering the fruits and capturing the animals which she has offered for his sustenance, he has, with advancing civilization, engaged in a contest to subdue the earth and possess it. His warfare indeed has often been a blind one, successful for the moment, but leading to sure and sad disaster. He has, for instance, stripped off the woodland from many a region of hill and mountain, gaining his immediate object in the possession of their stores of timber, but thereby laying bare the slopes to parching droughts or fierce rains. Countries once rich in beauty, and plenteous in all that was needful for his support, are now burnt and barren, or washed bare of their soil. It is only in comparatively recent years that he has learnt the truth of the aphorism—"*Homo Naturæ minister et interpres.*"

But now, when that truth is coming more and more to be recognized and acted on, man's influence is none the less marked. His object still is to subdue the earth, and he attains it, not by setting nature and her laws at defiance, but by enlisting her in his service. Within the compass of this volume it is impossible to give more than merely a brief outline of so vast a subject.[1] The action of man is necessarily confined mainly to the land, though it has also to some extent influenced the marine fauna. It may be witnessed on climate, on the flow of water, on the character of the terrestrial surface, and on the distribution of life.

1. On Climate.—Human interference affects meteorological conditions—(1) by removing forests and laying bare to the sun and winds areas which were previously kept cool and damp under trees, or which, lying on the lee side, were protected from tempests; as already stated, it is supposed that the wholesale destruction of the woodlands formerly existing in countries bordering the Mediterranean has been in part the cause of the present desiccation of these districts; (2) by drainage, the effect of this operation being to remove rapidly the discharged rainfall, to raise the temperature of the soil, to lessen the evaporation, and thereby to diminish the rainfall and somewhat increase the general temperature of a country; (3) by the other processes of agriculture, such as the transformation

[1] See Marsh's "Man and Nature," a work which, as its title denotes, specially treats of this subject, and of which a new and enlarged edition was published in 1874 under the title of "The Earth as modified by Human Action." It contains a copious bibliography. See also Rolleston, *Jour. Roy. Geog. Soc.* xlix. p. 320, and works cited by him, particularly De Candolle, "Géographie botanique raisonnée," 1855; Unger's "Botanische Streifzüge," in *Sitzber. Vienna Acad.* 1857-1859; J. G. St. Hilaire, "Histoire naturelle générale des Règnes Organiques," tom. iii. 1862; Oscar Peschel, "Physische Erdkunde;" Link, "Urwelt und Alterthum" (1822).

of moor and bog into cultivated land, and the clothing of bare hill-sides with green crops or plantations of coniferous and hardwood trees.

2. On the Flow of Water.—(1) By increasing or diminishing the rainfall man directly affects the circulation of water over the land. (2) By the drainage operations which cause the rain to run off more rapidly than before, he increases floods in rivers. (3) By wells, bores, mines, or other subterranean works, he interferes with underground waters and consequently with the discharge of springs. (4) By embanking rivers he confines them to narrow channels, sometimes increasing their scour, and enabling them to carry their sediment further seaward, sometimes causing them to deposit it over the plains and raise their level.

3. On the Surface of the Land.—Man's operations alter the aspect of a country in many ways:—(1) by changing forest into bare mountain, or clothing bare mountains with forest; (2) by promoting the growth or causing the removal of peat-mosses; (3) by heedlessly uncovering sand-dunes, and thereby setting in motion a process of destruction which may convert hundreds of acres of fertile land into waste sand, or by prudently planting the dunes with sand-loving herbage or pines, and thus arresting their landward progress; (4) by so guiding the course of rivers as to make them aid him in reclaiming waste land, and bringing it under cultivation; (5) by piers and bulwarks, whereby the ravages of the sea are stayed, or by the thoughtless removal from the beach of stones which the waves had themselves thrown up, and which would have served for a time to protect the land; (6) by forming new deposits either designedly or incidentally. The roads, bridges, canals, railways, tunnels, villages, and towns with which man has covered the surface of the land will in many cases form a permanent record of his presence. Under his hand the whole surface of civilized countries is very slowly covered by a stratum, either formed wholly by him, or due in great measure to his operations, and containing many relics of his presence. The soil of old cities has been increased to a depth of many feet by the rubbish of his buildings; the level of the streets of modern Rome stands high above that of the pavements of the Cæsars, and this again above the roadways of the early republic. Over cultivated fields potsherds are turned up in abundance by the plough. The loam has risen within the walls of our graveyards, as generation after generation has mouldered there into dust.

4. On the Distribution of Life.—It is under this head, perhaps, that the most subtle of human influences come. Some of man's doings in this domain are indeed plain enough, such as the extirpation of wild animals, the diminution or destruction of some forms of vegetation, the introduction of plants and animals useful to himself, and especially the enormous predominance given by him to the cereals and to the spread of sheep and cattle. But no such extensive disturbance of the normal conditions of the distribution of

life can take place without carrying with it many secondary effects, and setting in motion a wide cycle of change and of reaction in the animal and vegetable kingdoms. For example, the incessant warfare waged by man against birds and beasts of prey in districts given up to the chase leads sometimes to unforeseen results. The weak game is allowed to live, which would otherwise be killed off and give more room for the healthy remainder. Other animals, which feed perhaps on the same materials as the game, are by the same cause permitted to live unchecked, and thereby to act as a further hindrance to the spread of the protected species. But the indirect results of man's interference with the *régime* of plants and animals still require much prolonged observation.[1]

This necessarily imperfect outline may suffice to indicate how important is the place filled by man as a geological agent, and how in future ages the traces of his interference may introduce an element of difficulty or uncertainty into the study of geological phenomena.

[1] See on the subject of man's influence on organic nature, the paper by Professor Rolleston, quoted in a previous note, and the numerous authorities cited by him.

BOOK IV.

GEOTECTONIC (STRUCTURAL) GEOLOGY,

OR THE ARCHITECTURE OF THE EARTH'S CRUST.

THE nature of minerals and rocks and the operations of the different agencies by which they are produced and modified having been discussed in the two foregoing books, there remains for consideration the manner in which these materials have been arranged so as to build up the crust of the earth. Since by far the largest portion of this crust consists of sedimentary or aqueous rocks, it will be of advantage to treat of them first, noting both their original characters as resulting from the circumstances under which they were formed, and the modifications subsequently effected upon them. Many superinduced structures, not peculiar to sedimentary, but occurring more or less markedly in all rocks, may be conveniently described together. The distinctive characters of the igneous or eruptive rocks, as portions of the architecture of the crust, will then be described; and lastly, those of the crystalline schists and other associated rocks to which the name of metamorphic is usually applied.

PART I.—STRATIFICATION AND ITS ACCOMPANIMENTS.

The term "stratified," so often applied as a general designation to the aqueous or sedimentary rocks, expresses their leading structural feature. Their materials, laid down for the most part on the bed of the sea and the floors of lakes and rivers under conditions which have been already discussed in Book III., are disposed in layers or strata, an arrangement characteristic of them alike in hand-specimens and in cliffs and mountains (Figs. 182 and 183). Not that every morsel of aqueous rock exhibits evidence of stratification. But it is this feature which is least frequently absent. The general characters of stratification will be best understood from an explanation of the terms by which they are expressed.

Forms of Bedding.—Laminæ are the thinnest paper-like layers in the planes of deposit of a stratified rock. Such fine layers only occur where the material is fine-grained, as in mud or shale, or where fine scales of some mineral have been plentifully deposited, as in micaceous sandstone. In some laminated rocks the laminæ cohere so firmly that they can hardly be split open, and the rock will

break more readily across them than in their direction. More usually, however, the planes of lamination serve as convenient divisional surfaces by means of which the rock can be split open. The cause of this structure has been generally assigned to intermittent deposit, each lamina being assumed to have partially consolidated before its

FIG. 182.—SEA-CLIFF SHOWING A SERIES OF STRATIFIED ROCKS (*B.*).

successor was laid down upon it. Mr. Sorby, however, has recently suggested that in fine argillaceous rocks it may be a kind of cleavage-structure (see p. 310) due to the pressure of the overlying rocks with the consequent squeezing out of insterstitial water and the rearrangement of the argillaceous particles in lines perpendicular to the pressure.[1]

Much may be learnt as to former geographical and geological changes by attending to the characters of the strata. In Fig. 183, for example, there is evidence of a gradual diminution of movement in the waters in which the layers of sediment were deposited. The conglomerate (*a*) points to currents of some force; the sandstones (*b c d*) mark a progressive quiescence and the advent of finer sediment; the shales (*e*) show that by the time they were formed, only very fine mud was borne along; while the shell-limestone (*f*) proves that the water no longer carried sediment, but was clear enough to permit of an abundant growth of marine organisms. The existence, therefore, of alternations of fine laminæ of deposit may be conceived as pointing to tranquil conditions of slow intermittent sedimentation, where silt has been borne at intervals and has fallen over the same area of undisturbed water. Regularity of thickness and persistence of lithological characters among the laminæ may be taken to indicate periodic currents, of approximately equal force, from the same quarter. In some cases successive tides in a sheltered estuary may have been the agents of deposition. In others the sediment was doubtless brought by recurring river-floods. A great thickness of laminated rock, like the massive shales of Palæozoic formations, suggest a prolonged period of quiescence, and probably in most cases, slow, tranquil subsidence of the sea-floor. On the other hand,

[1] *Quart. Journ. Geol. Soc.* xxxvi. p. 67 (1880).

the alternation of thin bands of laminated rock with others, coarser in texture and non-laminated, indicates considerable oscillation of currents from different quarters bearing various qualities and amounts of sediment.

Strata or Beds are layers of rock varying from an inch or less up to many feet in thickness. A stratum may be made up of numerous laminæ, if the nature of the sediment and mode of deposit have favoured the production of this structure, as has commonly been the case with the finer kinds of sediment. In materials of coarser grain, the strata, as a rule, are not laminated, but form the thinnest parallel divisions. Strata, like laminæ, sometimes cohere firmly, but are commonly separable with more or less ease from each other. In the former case we may suppose that the lower bed before its consolidation was followed by the deposit of the upper. The common merging of a stratum into that which overlies it must no doubt be regarded as evidence of more or less gradual change in

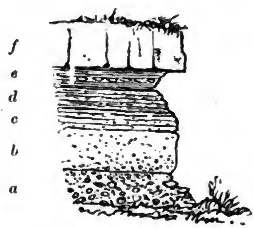


Fig. 183.—Section of Stratified Rocks.

a, conglomerate; *b*, thick-bedded pebbly sandstone; *c*, thin-bedded sandstone; *d*, shelly sandstone; *e*, shale with ironstone nodules; *f*, limestone with marine organisms.

the conditions of deposit. Where the overlying bed is abruptly separable from that below it, the interval was probably of some duration, though occasionally the want of cohesion may arise from the nature of the sediment, as for instance where an intervening layer of mica flakes has been laid down. A stratum may be one of a series of similar beds in the same mass of rock, as where a thick sandstone includes many individual strata, varying considerably in their respective thicknesses; or it may be complete and distinct in itself, as where a band of limestone or ironstone runs through the heart of a series of shales. As a general rule, the conclusion appears to be legitimate that stratification, when exceedingly well-marked, indicates slow intermittent deposit, and that when weak or absent it points to more rapid deposit, intervals and changes being necessary for the production of a distinctly stratified structure.

Lines due to original stratification must be carefully distinguished from other divisional planes which, though somewhat like them, are of entirely different origin. Three distinct kinds of

fissility may be recognized among rocks. 1st, *lamination* of original deposit, which has just been described; 2nd, *cleavage*, as in slate; 3rd, *foliation*, as in schists. Occasionally, by the development of steam-holes or spherulitic concretions in lavas, and the drawing out of these into planes during the movement of the molten mass, a kind of fissility is produced which at first might be mistaken for the lamination of deposit. Close-set joints likewise give rise to divisional planes, which now and then may deceive an observer by their resemblance to stratification.

Originally the planes of stratification, in the great majority of cases, were nearly horizontal. As most sedimentary rocks are of marine origin, and have accumulated on the shallower slopes of the sea-floor, they must have had from the first a slight inclination seawards; but, save on rapidly shelving shores, the angle of declivity has been usually so slight as to be hardly appreciable by the eye. Slight departures from this predominant horizontality would be caused where sediment accumulated unequally, or where the floor on which deposition took place was of an undulating or more markedly uneven character.

False-bedding, Current-bedding.—Some strata, particularly sandstones, are marked by an irregular lamination, wherein the

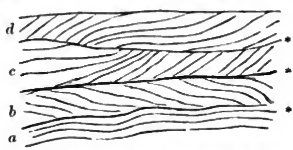


FIG. 184.—SECTION OF FALSE-BEDDED STRATA.

laminæ, though for short distances parallel to each other, are oblique to the general stratification of the mass, at constantly varying angles and in different directions (*a b c d* in Fig. 184). This structure, known as false-bedding or current-bedding, points to frequent changes in the direction of the currents by which the sediment was carried along and deposited. Sand pushed over the bottom of a sheet of water by varying currents tends to accumulate irregularly in bands and ridges, which often advance with a steep slope in front. The upper and lower surfaces of the bank or bed of sand (* * in Fig. 184) may remain parallel with each other as well as with the underlying bottom (*a*), yet the successive laminæ composing it may lie at an angle of 30° or even more. We may illustrate this structure by the familiar formation of a railway embankment. The top of the embankment on which the permanent way is to be laid, is kept level; but the advancing end of the earth-work shows a steep slope over which the workmen are constantly discharging waggon-loads of rubbish. Hence the embankment, if cut open longitudinally, would present a "false-bedded" structure, for it would be found to consist

of many irregular layers inclined at a high angle in the direction in which the formation of the mound had advanced. Among geological formations of all ages, occasional sections of the upper surfaces of such false-bedded strata show the singular irregularity of the structure, and bring vividly before the imagination the feeble shifting currents by which the sediment was drifted about in the shallow water where it accumulated (Fig. 185). A noticeable feature is the

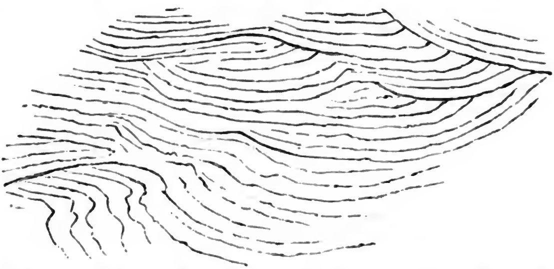


Fig. 185.—Plan of Upper Surface of a False-bedded Coal-measure Sandstone, Nolton Haven, Pembrokeshire. (By the late Professor John Phillips.)

markedly lenticular character of false-bedded strata. Even where the usual diagonal lamination is feeble or absent this lenticular structure may remain distinct (Fig. 186). Examples may also be observed, in which, while all the beds are well laminated, in some

Fig. 186.—False-Bedded Strata, Old Red Sandstone, Ross, Herefordshire. (By the late Sir Henry James, R.E.)

the laminæ run parallel with the general bedding and in others obliquely (Fig. 187). Though current-bedding is most frequent among sandstones, or markedly arenaceous strata, it may be observed occasionally in detrital formations of organic origin, as in a section (Fig. 188) by De la Beche, where a portion of one of the calcareous members of the Jurassic series of England, consists of beds composed mostly of organic fragments with a strongly marked

current-bedding (*a a*), while others, formed of muddy layers and not obliquely laminated (*b b*), point to intervals when, with the cessation

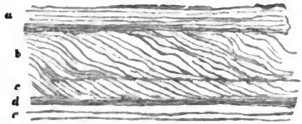


FIG. 187.—ORDINARY LAMINATION AND CURRENT-LAMINATION, UPPER OLD RED SANDSTONE, CLOWES BAY, WATERFORD (*B.*).

a, *d*, *e*, beds of sand and silt deposited horizontally and apparently from mechanical suspension; *b*, *c*, beds of sand which have been pushed along the bottom.

of the silt-bearing currents, the water became still enough to allow the mud suspended in it to settle on the bottom.[1]

Instances may be noticed where the diagonal lamination is con-

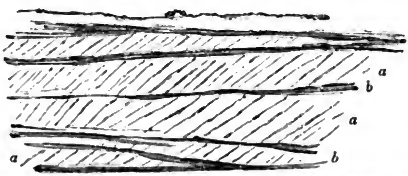


FIG. 188.—SECTION IN THE FOREST MARBLE, THE BUTTS, FROME, SOMERSET (*B.*).

a, *a*, beds formed of broken shells, fish-teeth, pieces of wood, and oolitic grains; *b*, *b*, layers of clay.

torted as well as steeply inclined, or where highly contorted beds are interposed between others which are undisturbed and horizontal. Curved and contorted lamination is of frequent occurrence among

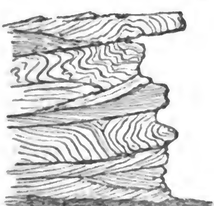


FIG. 189.—CONTORTED FALSE-BEDDING, CAMBRIAN SANDSTONE, GAIRLOCH.

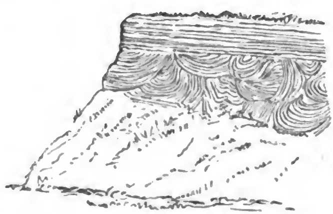


FIG. 190.—CONTORTED POST-TERTIARY SANDS AND CLAYS, NEAR FORRES.

palæozoic sandstones. In Fig. 189, an example is given from one of the oldest formations in Britain, and in Fig. 190 another from one of the

[1] Geological Observer, p. 536.

youngest. The cause of this structure is not well understood. Among the sands and clays of the glacial deposits local examples of contortion occur, which may be accounted for, in some cases, by the intercalation and subsequent melting of sheets of frozen mud; in others by the stranding of heavy masses of drift ice upon still unconsolidated sand and mud. It is possible that some of the extraordinary labyrinthine and complex contortions of schistose rocks may be due to the subsequent crumpling of strata already full of this diagonal contorted lamination.

Irregularities of Bedding due to Inequalities of Deposition or of Erosion.—A sharp ridge of sand or gravel may be laid down under water by current-action of some strength. Should the motion of the water diminish, finer sediment may be brought to the place and be deposited around and above the ridge. In such a case the stratification of the later accumulation will end

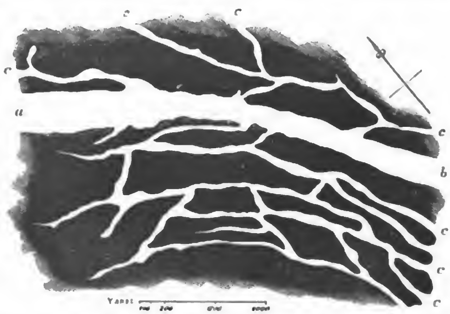


Fig. 191.—Plan of Channels in Coal, Forest of Dean (after Buddle).

off abruptly against the flanks of the older ridge, which will appear to rise up through the overlying bed. Appearances of this kind are not uncommon in coal-fields, where they are known to the miners as "rolls," "swells," or "horses' backs." A structure exactly the reverse of the preceding where a stratum has been scooped out before the deposition of the layers which cover it, has also often been observed in mining for coal, when it is termed a "want." Channels have been cut out of a coal-seam, or rather out of the bed of vegetation which ultimately became coal, and these winding and branching channels have been filled up with sandy or muddy sediment. The accompanying plan (Fig. 191) represents a portion of a remarkable series of such channels traversing the Coleford High Delf coal-seam in the Forest of Dean. The chief one, locally known as the "Horse" (*a b*), has been traced for about two miles, and varies in width from 170 to 340 yards. It is joined by smaller tributaries (*c c*), which run for some way approximately parallel to it. The coal has either been prevented

from accumulating in contemporaneous water-channels, or, while still in the condition of soft bog-like vegetation, has been eroded by streamlets flowing through it.[1] A section drawn across such a buried channel exhibits the structure represented in Fig. 192, where a bed of fire-clay (*e*), full of roots and evidently an old soil, supports a bed of coal (*d*) and of shale (*c*), which, during the deposition of this series of strata, have been cut out into a channel at *f*. A deposition of sand (*b*) has then filled up the excavation, and a layer of mud (*a*) has covered up the whole.

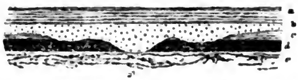


FIG. 192.—SECTION OF A CHANNEL IN A COAL-SEAM (*B.*).

Currents of very unequal force and transporting power may alternate in such a way that after fine silt has for some time been accumulated, coarse shingle may next be swept along, and may be so irregularly bedded with the softer strata as to simulate the behaviour of an intrusive rock (Fig. 193).[2] The section (Fig. 194), taken by De la Beche from a cliff of Coal-measures on the coast of Pembrokeshire, shows a deposit of shale (*a*) that during the course of its formation was eroded by a channel at *b*, into which sand was

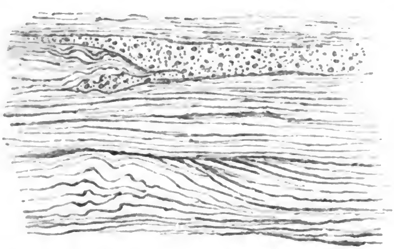


FIG. 193.—IRREGULAR BEDDING OF COARSE AND FINE LOWER SILURIAN DETRITUS. FLANKS OF GLYDYR, N.E. OF SNOWDON (*B.*).

carried; after which, the deposit of fine mud recommenced, and similar shale as before was laid down upon the top of the sandy layer, until, by a more potent current, the shale deposit was cut away on the left side of the section and a series of sand beds (*c*) was laid down upon its eroded edges. An interruption of this kind, however, may not seriously disturb the earlier conditions of a deposit which, as shown in the same section, may be again resumed,

[1] Buddle, *Geol. Trans.* vi. (1842), p. 215.
[2] De la Beche, Geol. Observer, p. 533.

and new layers (*d*) may be laid down conformably over the whole. Among the lessons to be learnt from such sections of local irregularity, one of the most useful is the reminder, that the inclination of strata

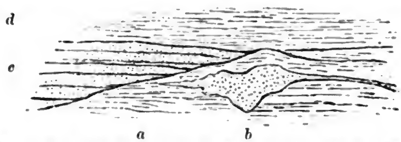


Fig. 194.—Contemporaneous Erosion and Deposit (*B.*).

may not always be due to subterranean movement. In Fig. 195, for example, the lower strata of shale and sandstone are nearly horizontal. The upper thick sandstone (*b'*) has been cut away towards the left, and a series of shales (*a'*) and a coal-seam (*c'*) have been deposited against and over it. If the sandstone was then level, the shales must have been laid down at a considerable angle, or if these were deposited in horizontal sheets, the earlier sandstone must have accumulated on a marked slope. As deposition continued, the in-

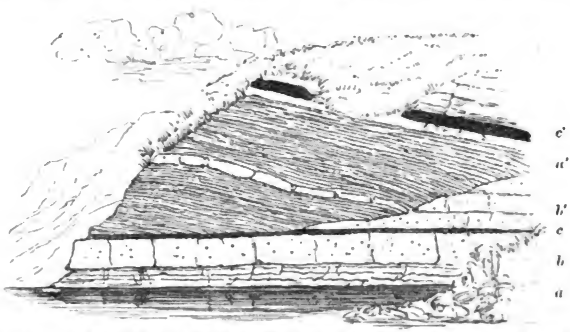


Fig. 195.—Contemporaneous Erosion with Inclined and Horizontal Deposits, in Coal Measures, Kello Water, Sanquhar, Dumfriesshire.
a', shales and ironstones; *b*, *b'*, sandstones; *c*, *c'*, coal-seams.

clined plane of sedimentation would gradually become horizontal until the strata became once more parallel with the series *a b c* below. A structure of this kind, not unfrequent in the Coal-measures, must be looked upon as a larger kind of false-bedding, where, however, terrestrial movement may sometimes have taken place.

In the instances here cited, it is evident that the erosion took place, in a general sense, during the same period with the accumulation of the strata. For after the interruption was covered

up sedimentation went on as before, and there is usually an obvious close sequence between the continuous strata. Though it may be impossible to decide as to the relative length of the interval that elapsed between the formation of a given stratum and that of the next stratum which lies upon its eroded surface, or to ascertain how much depth of rock has been removed in the erosion, yet, when the structure occurs among conformable strata, evidently united as one lithologically continuous series of deposits, we may reasonably infer that the missing portions are of small moment, and that the erosion was merely due to the irregular and more violent action of the very currents by which the sediment of the successive strata was supplied.

The case is very different when the eroded strata are inclined at a different angle from those above them, and are strongly marked off by lithological distinctions. In some of the coal-mines in central Scotland, for instance, deep channels have been met with entirely filled with sand, gravel, or clay belonging to the general superficial drift of the country. These channels have evidently been water-courses worn out of the Coal-measure strata at a comparatively recent geological period, and subsequently buried under the glacial accumulations. There is a complete discordance between them and the palæozoic strata below, pointing to the existence of a vast interval of time.

Surface-markings.—Ripple-mark.—The surface of many beds of sandstone is marked with lines of wavy ridge and hollow, such as may be seen on a sandy shore from which the tide has retired, on the floors of shallow lakes and of river pools, and on surfaces of dry wind-blown sand. Water (or air) gently agitated in a given direction, throws the surface of sediment into ripples, which tend to run at right angles to the course of movement. If the wind blows with little variation towards a given point, the sand ripples have a long gentle slope towards the wind, and a short steep slope away from it (Fig. 196). Considerable diversity in the form of the ripple (as at *a b c* in Fig. 197) may be observed, depending on conditions of wind, water, and sediment which have not been thoroughly studied. As the wind veers from point to point, producing corresponding changes in the direction of the water currents, the ripples on the bottom are not strictly parallel, but often coalesce, intersect, and undulate in their course. Their general direction, however, suffices to indicate the quarter whence the chief movement of the water has come. No satisfactory inference can be drawn from the existence of ripple-marks as to the precise depth of water in which the sediment was accumulated. As a rule, it is in water of only a few feet or yards in depth that this characteristic surface is formed. But it may be produced at any depth to which the agitation caused by wind on the upper waters may extend (p. 423).

An examination of a sandy beach brings before us many modifications of the perfect ripple-mark. The ridges may be seen to grow

more and more notched and irregular, until at last the beach seems to be dotted over with little, flat, dome-shaped mounds, or as if the ridges of the ripple-mark had been furrowed across. These modifications may be due to the partial effacement of the ridges by subsequent action of the water agitated by wind blowing from a different quarter. Such indications of shallow-water conditions may often be observed among old arenaceous deposits, as in the Cambrian and Silurian rocks. In like manner we may frequently detect, among these formations, small isolated or connected linear ridges (rill-marks) directed from some common quarter, like the current-marks frequently to be found behind projecting fragments of shell, stones, or bits of sea-weed on a beach from which the tide has just retired.

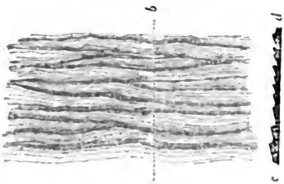


Fig. 196.—Plan and Section of Rippled Surface.

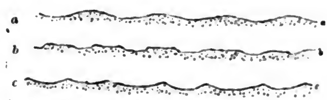


Fig. 197.—Sections of Ripple-marks.

On an ordinary beach each tide usually effaces the ripple-marks made by its predecessor and leaves a new series to be obliterated by the next tide. But where the markings are formed in water which is always receiving fresh accumulations of sediment, a rippled surface may be gently overspread by the descent of a layer of sediment upon it and may thus be preserved. Another series of ripples may then be made in the overlying layers, which in turn may be buried and preserved under a renewed deposit of sand. In this way a considerable thickness of such ripple-marked strata may be accumulated, as has frequently taken place among geological formations of all ages.

Sun-cracks, Rain-prints, Vestiges of former Shores.—One of the most fascinating parts of the work of a field-geologist consists in tracing the shores of former seas and lakes, and in endeavouring thereby to reconstruct the geography of successive geological periods. There are not a few pieces of evidence, which, though in themselves individually of apparently small moment, combine to supply him with reliable data. Among these he lays special emphasis upon the proofs that during their deposition strata have at intervals been laid bare to sun and air.

The nature and validity of the arguments founded on this evidence will be best realized by the student if he can make observations at the margin of the sea, or of any inland sheet of water, which from time to time leaves tracts of mud or fine sand exposed to sun and

rain. The way in which the muddy bottom of a dried-up pool cracks into polygonal cakes when exposed to the sun may be illustrated abundantly among sedimentary rocks. These desiccation-cracks, or sun-cracks (Fig. 198), could not have been produced so long as the sediment lay under water. Their existence therefore among any strata proves that the surface of rock on which they lie was exposed to the air and dried before the next layer of water-borne sediment was deposited upon it.

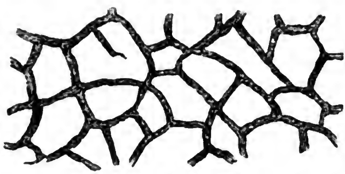


FIG. 198.—SUN-CRACKED SURFACE OF MUD OR MUDDY SAND.

With these markings are not infrequently associated prints of rain-drops. The familiar effects of a heavy shower upon a surface of moist sand or mud may be witnessed among rocks even as old as parts of the Cambrian system. In some cases the rain-prints are found to be ridged up on one side, in such a manner as to indicate that the rain-drops as they fell were driven aslant by the wind. The prominent side of the markings therefore indicates the side towards which the wind blew.

Numerous proofs of shallow shore-water, and likewise of exposure to the air, are supplied by markings left by animals. Castings, tubular burrows, and trails of worms, tracks of molluscs and crustaceans,

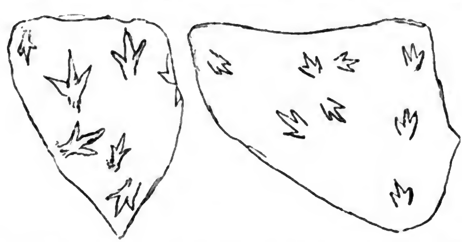


FIG. 199.—FOOTPRINTS FROM THE TRIASSIC SANDSTONE OF CONNECTICUT (HITCHCOCK).

fin-marks of fishes, footprints of reptiles, birds, and mammals, may all be preserved and give their evidence regarding the physical conditions under which sedimentary formations were accumulated. It may frequently be noticed that such impressions are associated with

ripple-marks, rain-prints, or sun-cracks (Fig. 200); so that more than one kind of evidence may be gleaned from a locality to show that it was sometimes laid bare of water.

These more striking indications of littoral conditions being comparatively infrequent, the geologist must usually content himself with tracing the gravelly detritus, which suggests, if it does not

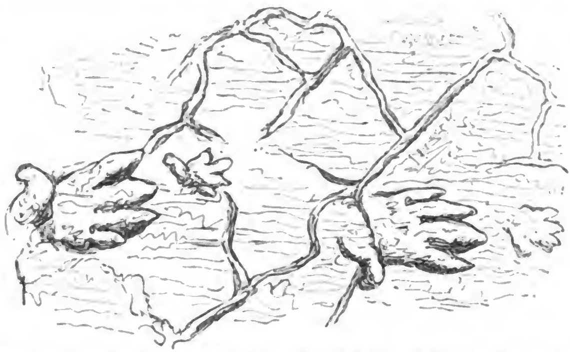


Fig. 200.—Footprints and Sun-cracks, Hildburghausen, Saxony (Sickler).

always prove, proximity to some former line of shore. Such a section for instance as that depicted in Fig. 201 may often be found, where lower strata (*a*) having been tilted, raised into land, and worn away, have yielded materials for a coarse littoral boulder-bed (*b*), over which, as it was carried down into deeper and clearer water, limestone eventually accumulated. Beds of conglomerate, especially where,

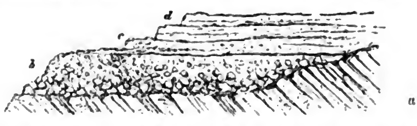


Fig. 201.—Section of a Beach of early Mesozoic Age, near Clifton, Bristol (*B.*)

a, Carboniferous limestone; *b*, dolomitic conglomerate—a mass of boulders and angular fragments of *a* (some of them almost two tons in weight), passing up into finer conglomerate *c*, with sandstone and marl, and thence into dolomitic limestone *d*.

as in this example, they accompany an unconformability in the stratification, are of much service in tracing the limits of ancient seas and lakes (see Part X.).

G a s - s p u r t s.—The surfaces of some strata, usually of a dark colour and containing organic matter, may be observed to be raised into little heaps of various indefinite shapes, not like the

heaps associated with worm burrows, connected with pipes descending into the rock, nor composed of different material from the surrounding sandstone or shale. These may be conjectured to be due to the intermittent escape of gas from decomposing organic matter in the original sand or mud, as we may sometimes witness in operation among the mud flats of rivers and estuaries, where much organic matter is decomposing among the sediment. On a small scale these protrusions of the upper surface of a deposit may be compared with the mud-lumps at the mouths of the Mississippi, already described (p. 386).

Concretions.—Many sedimentary rocks, more particularly clays, ironstones, and limestones, exhibit a concretionary structure. This arrangement may be part of the original sedimentation, or may be due to subsequent segregation from decomposition round a centre. Concretionary structures of contemporaneous origin, particularly in calcareous materials, may lie so closely adjacent as to form continuous or nearly continuous beds (Fig. 202). The magnesian

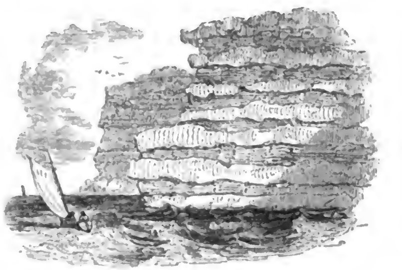


FIG. 202.—SECTION OF ALTERNATIONS OF SHALE AND CONCRETIONARY LIMESTONE (*B.*).

limestone of Durham is built up of variously shaped concretionary masses, sometimes like cannon-balls, grape-shot, or bunches of coral. Connected with concretionary beds are the seams of gypsum, which may occasionally be observed to send out veins into other gypsum beds above and below them. De la Beche describes a section at Watchet, Somersetshire, where, amid the old Triassic marls (*b b* in Fig. 203), beds of gypsum (*a a*) connect themselves by means of fibrous veins with the overlying and underlying beds.

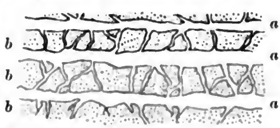


FIG. 203.—SECTION OF BEDS AND CONNECTING STRINGS OF GYPSUM IN THE TRIAS, WATCHET, SOMERSETSHIRE (*B.*).

The most frequent form of concretions is that of isolated spherical, elliptical, or variously shaped nodules, disposed in certain layers

of a stratum or dispersed irregularly through it (Fig. 204). They most commonly consist of ferrous or calcic carbonates, or of silica. Many clay-ironstone beds assume a nodular form, and this mineral occurs abundantly in the shape of separate nodules in shales and clay-rocks. The nodules have frequently formed round some organic body, such as a fragment of plant, a shell, bone, or coprolite. That the carbonate was slowly precipitated during the formation of the bed of shale in which its nodules lie may often be satisfactorily proved by the lines of deposit passing continuously through the nodules (Fig. 205). In many cases the internal first-formed parts

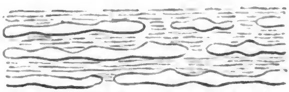


Fig. 204.—Concretions of Limestone in Shale.

Fig. 205.—Concretions surrounding Organic Centres, and exhibiting the Continuation of the Lines of Stratification of the surrounding Shales.

of a nodule have contracted more than the outer and more compact crust; and have cracked into open polygonal spaces which are commonly filled with calcite (Fig. 30). Such *septarian nodules,* whether composed of clay-ironstone or limestone, are abundant in many shales, as in the Carboniferous and Liassic series of England.

Alluvial clays sometimes contain fantastically shaped concretions due to the consolidation of the clay by a calcareous or ferruginous cement round a centre. These are known in Scotland as fairy-stones, in the Valley of the Rhine as Löss-puppen, Löss-männchen, and in Finland as Imatra-stones (Fig. 206). They not uncommonly show the bedding of the clay in which they may have been formed. Their quaint imitative forms have naturally given rise to a popular belief that they are petrifactions of various kinds of organic bodies and even of articles of human manufacture. In Norway they enclose remains of fishes and other organisms.[1]

Concretions of silica occur in limestone of many geological ages (p. 117). The flints of the English chalk are a familiar example, but similar siliceous concretions occur in Carboniferous and Lower Silurian limestones. The silica in these cases has not infrequently been deposited round organic bodies, such as sponges, sea-urchins, and mollusca, which are completely enveloped in it, and have even themselves been silicified. Iron-disulphide often assumes the form of concretions, more particularly among clay-rocks, and these, though presenting many eccentricities of shape—round like pistol-shot or cannon-balls, kidney-shaped, botryoidal, &c.—agree in usually possessing an internal fibrous radiated structure. Phosphate of lime is found as concretions in formations where the coprolites and bones of reptiles and other animals have been collected together.

Concretions produced subsequently to the formation of the rock

[1] Kjerulf, "Geologie des südl. und mittl. Norwegens" (1880), p. 5.

occur in some sandstones, which, when exposed to the weather, decompose into large round balls. In other instances, a ferruginous cement is gradually aggregated by percolating water in lines which curve round so as to enclose portions of the rock. These lines, owing to abstraction of iron from within the spheroid and partly from without, harden into dark crusts, inside of which the sandstone becomes quite bleached and soft.[1] Some shales exhibit a concretionary structure in a still more striking manner, inasmuch as the concretions consist of the general mass of the laminated shale,

FIG. 206.—CLAY CONCRETIONS OF ALLUVIUM. (NAT. SIZE.)

and the lines of stratification pass through them and mark them out distinctly as superinduced upon the rock. Examples of this structure are not infrequent among the argillaceous strata of the Carboniferous system. The concretionary olive-green shales and mudstones of the Ludlow group, in the Upper Silurian system, exhibit on weathered surfaces, all the way from South Wales into central Scotland, a peculiar structure which consists in the development of concentric spheroids varying from less than an inch up to several feet in diameter, the successive shells being separated from each other by a fine dark ferruginous film. The lines of stratification are sometimes well marked by layers of fossils, but the rock splits up mainly along the curved surfaces separating the concentric shells. Concretionary

[1] See Penning, *Geol. Mag.* Dec. 2, iii. May, 1876.

structures are found also in rocks formed from chemical precipitation, as for instance in beds of rock-salt. The pseudo-concretions probably due to pressure (stylolites) have been already described (p. 313).

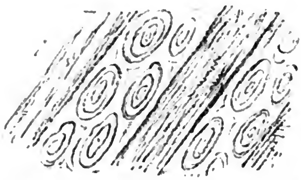


Fig. 207.—Concretionary Structure in Upper Silurian Shales, Cwm-ddu, Llangammarch, Brecknockshire (*B.*).

Alternations and Associations of Strata.—Though great variations occur in the nature of the strata composing a mass of sedimentary rocks, it may often be observed that certain repetitions occur. Sandstones, for example, are found to be interleaved with shale above, and then to pass into shale; the latter may in turn become sandy at the top and be finally covered by sandstone, or may assume a calcareous character and pass up into limestone. Such alternations bring before us the conditions under which the sedimentation took place. A sandstone group indicates water of comparatively little depth, moved by changing currents, bringing the sand now from one side now from another. The passage of such a group into one of shale points to a diminution in the motion and transporting power of the water, perhaps to a sinking of the tract, so that only fine mud was intermittently brought into it. The advent of limestone above the shale serves to show that the water cleared, owing to a deflection of the sediment-carrying currents, or to continued and perhaps more rapid subsidence, and that foraminifera, corals, crinoids, mollusca, or other lime-secreting organisms, established themselves upon the spot. Shale overlying the limestone would tell of fresh inroads of mud, which destroyed the animal life that had been flourishing on the bottom; while a return of sandstone beds would mark how, in the course of time, the original conditions of troubled currents and shifting sandbanks returned. Such alternating groups of sandy, calcareous, and argillaceous strata are well illustrated among the Jurassic formations of England (Fig. 208).

Certain kinds of strata commonly occur together, because the conditions under which they were formed were apt to arise in succession. One of the most familiar examples is the association of coal and fire-clay. A seam of coal is almost invariably found to lie on a bed of fire-clay, or on some argillaceous stratum. The reason of this union becomes at once apparent when we learn that the fire-clay was the soil on which the plants grew that went to form the coal. Where the clay was laid down under suitable circumstances, vegeta-

tion sprang up upon it. This appears to have taken place in wide shallow lagoon-like expansions of the sea, bordering land clothed with dense vegetation, and to have been accompanied by slow, intermittent but prolonged subsidence of the sea-bottom. Hence, during pauses

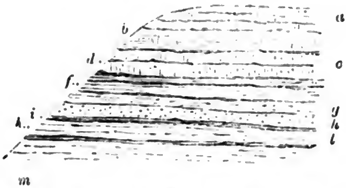


FIG. 208.—SECTION OF STRATA FROM THE BASE OF THE LIAS TO THE TOP OF THE TRIAS, SHEPTON MALLET (*B.*).

a, Grey Lias limestone and marls; *b*, earthy whitish limestone and marls; *c*, earthy white limestone; *d*, arenaceous limestone; *f*, grey marls; *g*, red marls; *h*, sandstone with calcareous cement; *i*, blue marl; *k*, red marl; *l*, blue marl; *m*, red marls.

of the downward movement, when the water shoaled, an abundant growth of water-loving or marshy plants sprang up on the muddy bottom, somewhat like the mangrove swamps of the present day, and continued to flourish until the muddy soil was exhausted,[1] or until subsidence recommenced and the matted jungles, carried under the water, were buried under fresh inroads of sand or mud. Every coal-field contains a succession of buried forests with a constant repetition of the same kinds of intervening strata (Fig. 209).

For obvious reasons conglomerate and sandstone occur together rather than conglomerate and shale. The agitation of the water which could form and deposit coarse detritus, like that composing conglomerate, was too great to admit of the accumulation of fine silt. On the other hand, we may look for shale or clay rather than sandstone as an accompaniment of limestone, inasmuch as when the gentle currents by which fine argillaceous silt was carried in suspension ceased, they would be succeeded by intervals of quiet clearing of the water, during which calcareous material might be elaborated either chemically or by the action of living organisms.

Relative persistence of Strata.—A little reflection will convince the student that all sedimentary rocks must thin out and disappear, and that even the most persistent, when regarded on the great scale, are local and lenticular accumulations. Derived from the degradation of land, they have always accumulated near land. They are necessarily thickest in mass as well as coarsest in texture nearest to the source of supply, and become more attenuated and fine-grained as they recede from it. We have only to observe what

[1] Sterry Hunt has called attention to the fact that the underclays of the Coal-measures have generally been deprived of their alkalies by the vegetable growth which they supported.

takes place at the present time on lake-bottoms, estuaries, or sea-margins to be assured that this is now, and must always have been, the law of sedimentation.

But while all sedimentary deposits must be regarded as essen-

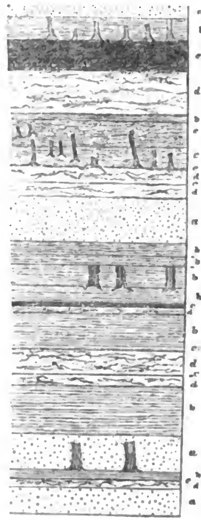


FIG. 209.—SUCCESSION OF BURIED COAL GROWTHS AND ERECT TREE-STUMPS, SYDNEY COAL-FIELD, CAPE BRETON (R. BROWN).[1]

a, sandstones; *b*, shales; *c*, coal-seams; *d*, beds containing roots and stumps *in situ*.

tially local, some kinds possess a far greater persistence than others. As a general rule it may be said that the coarser the grain the more local the extent of a rock. Conglomerates are thus by much the most variable and inconstant of all sedimentary formations. They suddenly sink down from a thickness of several hundred feet to a few yards, or die out altogether, to reappear perhaps further on, in the same wedge-like fashion. Sandstones are less liable to such extremes of inconstancy, but they too are apt to thin away and to swell out again. Shales are much more persistent, the same zone being often traceable for many miles. Limestones sometimes occur in thick local masses, as among the Silurian formations, but they often also display remarkable continuity. Three thin limestone bands, each of them only two or three feet in thickness, and separated

[1] See R. Brown, *Quart. Journ. Geol. Soc.* vi. p. 115, and De la Beche, "Geol. Observer," p. 505.

by a considerable thickness of intervening sandstones and shales, can be traced through the coal-fields of central Scotland over an area of at least 1000 square miles. Coal-seams also possess great persistence. The same seams, varying slightly in thickness and quality, may often be traced throughout the whole of an extensive coal-field.

What is thus true of individual strata may be affirmed also of groups of such strata. A thick mass of sandstone will be found as a rule to be more continuous than one of conglomerate, but less so than one of shale. A series of limestone-beds usually stretches further than either arenaceous or argillaceous sediments. But even to the most extensive stratum or group of strata there must be a limit. It must end off and give place to others, either suddenly, as a bank of shingle is succeeded by the sheet of sand heaped against its base, or, as is more usual, very gradually, by insensibly passing into other strata on all sides.

Great variations in the character of stratified rocks may frequently be observed in passing from one part of a country to another along the outcrop of the same rocks. Thus at one end we may meet with a thick series of sandstones which, traced in a certain direction,

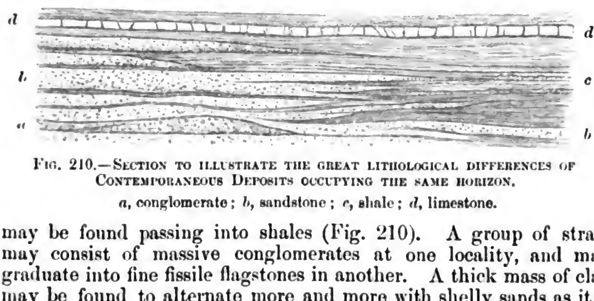


FIG. 210.—SECTION TO ILLUSTRATE THE GREAT LITHOLOGICAL DIFFERENCES OF CONTEMPORANEOUS DEPOSITS OCCUPYING THE SAME HORIZON.

a, conglomerate; *b*, sandstone; *c*, shale; *d*, limestone.

may be found passing into shales (Fig. 210). A group of strata may consist of massive conglomerates at one locality, and may graduate into fine fissile flagstones in another. A thick mass of clay may be found to alternate more and more with shelly sands as it is traced outward, until it loses its argillaceous nature altogether.

FIG. 211.—SECTION NEAR BRISTOL TO SHOW HOW CONGLOMERATE MAY PASS INTO CLAY ALONG THE SAME HORIZON.

B. Blaize Castle Hill; *s*, Mount Skitham (*B.*).

Interesting illustrations of such arrangements occur in the south-west of England, where what are now groups of hills, like the Mendip, Malvern, and other eminences, formerly existed as islands in the Mesozoic sea. De la Beche pointed out that the upturned Carboniferous limestone (*a a* in Fig. 211) has formed the shore against

which the coarse shingle of the dolomitic conglomerate (*b b*) accumulated; that the latter, traced away from its shore-line, passes on the same plane into red marl (*c*), and that during a gradual subsidence, the clays and limestones of the Lias (*d*) crept over the depressed shore-line. He likewise called attention to the important fact that, in such cases, a continuous zone of conglomerate may belong to many successive horizons. In Fig. 212 a section is given from one of the islands in the south-west of England, round which the Trias and Lias were deposited. Denudation has stripped off a portion of the overlying red marls. If the rest of the section to the left of the dotted line *d d* were removed, there would remain a continuous mass of conglomerate, which, in default of other evidence to the contrary, would be regarded as one bed laid down upon the sloping surface of limestone, instead of what it really is, a series of shore gravels piled upon each other, and belonging to a consecutive series of deposits.

Mere difference of lithological character, even within a limited geographical space, does not necessarily mean diversity of age. At the present time coarse shingle may be formed along the beach at

Fig. 212.—Section of Part of the Flank of the Mendip Hills (*B.*), showing the Carboniferous Limestone (*a a*) overlaid by dolomitic conglomerate (*b b*) and that by red marls (*c*).

the same time that the finest mud is being laid down on the same sea-bottom further from land. The existing differences of character between the deposits of the shore and of the opener sea would no doubt continue to be maintained, with slight geographical displacements, even if the whole area were undergoing subsidence, so that a thick group of littoral beds might gather in one tract and of deeper-water accumulations at another. Among the formations of former geological periods the same conditions of deposit appear sometimes to have continued for enormous periods. The thick Carboniferous Limestone of western Europe evidently accumulated during a slow subsidence, when the same conditions of clear water with abundant growth of crinoids, corals, &c., continued for a period vast enough to admit of the gradual growth of thousands of feet of calcareous matter. Traced northwards into Scotland this massive limestone is gradually replaced by sandstones, shales, ironstones, and coal-seams. These strata prove that the deeper and clearer water of Belgium, central England, and Ireland passed northwards into muddy flats and sandy shoals, which at one time were overspread with coal-growths, and at another, owing to more rapid subsidence, were depressed beneath the clearer sea which brought with it the

corals, crinoids, molluscs, &c., whose remains are now to be seen in intercalations of crinoidal limestone.

Overlap.—Sediment laid down in a subsiding region wherein the area of deposit is gradually increased, spreads over a progressively augmenting surface. Under such circumstances, the later portions of a formation or series of sedimentary accumulations will extend beyond the limits of the older parts, and will repose directly upon the shelving bottom, with none of these older strata underneath them. This relation, called Overlap (Fig. 213), in which the higher or newer members are said to "overlap" the older, may often be detected among formations of all geological ages. It brings before us the shore-line of ancient land-surfaces, and shows how, as these sank under water, the gravels, sands, and silts gradually advanced and covered them.

FIG. 213.—SECTION OF OVERLAP IN THE LOWER JURASSIC SERIES OF THE SOUTH-WEST OF ENGLAND (*B.*).

The Old Red Sandstone (*c*), Lower Limestone Shale (*b*), and Carboniferous Limestone (*a*) having been previously upraised and denuded, the older beaches (*d m*) laid down upon them were successively covered by conformable Jurassic beds. The Lias (*e*), with its upper sands (*f*), is overlapped by the extension of the Inferior Oolite (*g*) completely across their edges until this formation comes to rest directly on the Palæozoic strata at *n*. The corresponding extension of the overlying Fuller's earth (*h l*) and limestone (*i*) has been removed by denudation.[1]

Relative Lapse of Time represented by Strata and by the Intervals between them.—Of the absolute length of time represented by any strata or groups of strata no satisfactory estimates have yet been possible. Certain general conclusions may indeed be drawn, and comparisons may be made between different series of rocks. Sandstones full of false-bedding were probably accumulated more rapidly than finely-laminated shales or clays. It is not uncommon in certain Carboniferous sandstones to find huge sigillarioid and coniferous trunks imbedded in upright or inclined positions. Where, as in Fig. 214, the trees actually grew on the spot where their stems remain, it is evident that the rate of deposit of the sediment which entombed them must have been sufficiently rapid to have allowed a mass of twenty or thirty feet to accumulate before the decay of the wood. Of the durability of these ancient trees we of course know nothing; though modern instances are on record where, under certain circumstances, submerged trees may last for some centuries. We may conjecture that where stems are enveloped in one continuous stratum, the rate of accumulation was probably, on the whole, somewhat rapid. The general character of the strata among which such erect tree trunks occur obviously indicates ex-

[1] De la Beche, "Geol. Observer," p. 485.

tremely shallow water conditions with continuous or intermittent subsidence. Unless soon submerged, dead trees would be subject to speedy decomposition. It occasionally happens that an erect trunk has kept its position even during the accumulation of a series of strata

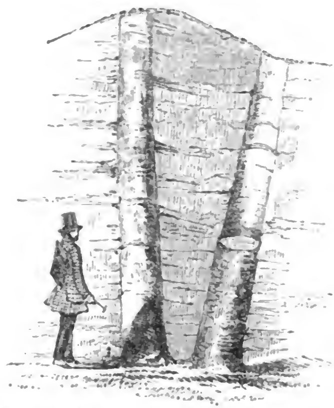


Fig. 214.—Elect Trunks of Sigillaria in Sandstone, Cwm Llech, Head of Swansea Valley, Glamorganshire. (Drawn by the late Sir W. E. Logan.)

These stems (the largest 5½ feet in circumference) formed part of a series in the same rock, their roots being imbedded in a seam of shale (an old soil) full of fern-leaves, &c. The specimens were removed to the Museum of the Royal Institution of South Wales at Swansea.[1]

around it (Fig. 215). We can hardly believe that in such cases any considerable number of years could have elapsed between the death of the tree and its final entombment. From the decayed condition of the interior of some imbedded trees, we may likewise infer that accumulation of sediment is not always an extremely slow process. Instances occur where, as in Fig. 216, while sand and mud have been accumulating round the submerged stem its interior has been rotting, so that eventually a mere hollow cylinder has been left, into which sediment and different plants (sometimes with the bodies of land animals) were introduced from above.[2] Large coniferous trunks (as in the neighbourhood of Edinburgh) have been imbedded in sandstone, and have had their internal microscopic structure well preserved. In such examples the drifted trees seem to have sunk with their heavier or root-end touching the bottom, and their upper end pointing upward in the direction of the current, like the snags

[1] De la Beche, *op. cit.* p. 501.
[2] The hollow tree-trunks of the Nova Scotian coal-fields have yielded a most interesting series of terrestrial organisms—land-snails and reptiles.

of the Mississippi, and to have been completely buried in sediment before decay.

Continuous layers of the same kind of deposit suggest a persistence of geological conditions; numerous alternations of different

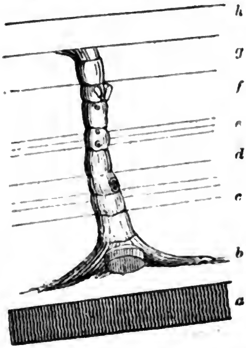


FIG. 215.—ERECT TREE-TRUNK RISING THROUGH A SUCCESSION OF STRATA, KILLINGWORTH COLLIERY, NEWCASTLE (*B.*).

a, High Main Coal-seam; *b*, bituminous shale; *c*, blue shale; *d*, compact sandstone; *e*, shales and sandstones; *f*, white sandstones; *g*, micaceous sandstone; *h*, shale.

kinds of sedimentary matter point to vicissitudes or alternations of conditions. As a rule, we should infer that the time represented by a given thickness of similar strata was less than that shown by the same thickness of dissimilar strata, because the changes needed to bring new varieties of sediment into the area of deposit would usually require the lapse of some time for their completion. But

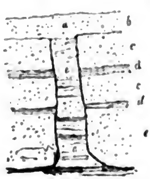


FIG. 216.—ERECT TREE-TRUNK (*a a*) IMBEDDED IN SANDSTONES (*c c*) AND SHALES (*d d*), ITS INTERIOR FILLED WITH DIFFERENT SANDY AND CLAYEY STRATA, AND THE WHOLE COVERED BY A SANDSTONE BED (*b*) (*B.*).

this conclusion might often be erroneous. It would be best supported when, from the very nature of the rocks, wide variations in the character of the water-bottom could be established. Thus a group of shales followed by a fossiliferous limestone would mark a period of

slow deposit and quiescence, almost always of longer duration than would be indicated by an equal depth of sandy strata, pointing to more active sedimentation. Thick limestones made up of organic remains which lived and died upon the spot, and whose remains are crowded together generation above generation, must have demanded prolonged periods for their formation.

But in all speculations of this kind we must bear in mind that the relative length of time represented by a given depth of strata is not to be estimated merely from thickness or lithological characters. It has already been pointed out that the interval between the deposit of two successive laminæ of shale may have been as long as, or even longer than, that required for the formation of one of the laminæ. In like manner, the interval needed for the transition from one stratum or kind of strata to another may often have been more than equal to the time required for the formation of the strata on either side. But the relative chronological importance of the bars or lines in the geological record can seldom be satisfactorily discussed merely on lithological grounds. This must mainly be decided on the evidence of organic remains, as will be shown in Book V. By this kind of evidence it can be made nearly certain that the intervals represented by strata were in many cases much shorter than those not so represented, —in other words, that the time during which no deposit of sediment went on was longer than that wherein deposit did take place.

Ternary Succession of Strata.—In following the order of sedimentation among the stratified rocks of the earth's crust, the observer will be led to remark a more or less distinct threefold arrangement or succession in which the sandy, muddy and calcareous sediments have followed each other. Professor Phillips and Mr. Hull have called attention to this structure, illustrating it by reference to the geological formations of Great Britain, while Professor Newberry, Dr. Sterry Hunt, and Principal Dawson have discussed it in relation to the stratigraphical series of North America. According to Mr. Hull a natural cycle of sedimentation consists of three phases: 1st, a lower stage of sandstones, shales, and other sedimentary deposits, representing prevalence of land with downward movement; 2nd, a middle stage, chiefly of limestone, representing prevalence of sea with general quiescence and elaboration of calcareous organic formations; 3rd, an upper stage, once more of mechanical sediments indicative of proximity to land.[1] Where the strata are interrupted by disturbance and unconformability, we may suppose the cycle of sedimentation to have been completed by upheaval after prolonged subsidence. But where the continuity of the formations is unbroken, as it is over such vast tracts in North America, upheaval is not required, and the facts seem explicable, as Phillips long ago showed, on

[1] Phillips, *Mem. Geol. Surv.* ii.; "Geol. Yorkshire," ii.; "Geol. Oxford," p. 293; Hull, *Quart. Journ. Sci.* July, 1869; Newberry, *Proc. Amer. Assoc.* 1873, p. 185; Hunt, *Geology of Canada*, 1863, p. 627; *Amer. Journ. Sci.* (2nd series), xxxv. p. 167; Dawson, *Q. J. Geol. Soc.* xxii. p. 102; *Acadian Geology*, p. 135.

the idea of prolonged but intermittent subsidence. Let us suppose a downward movement to commence, and to depress successive sheets of gravel, shingle, sand, and other shallow water accumulations, derived from the erosion of neighbouring land. If the depression be comparatively rapid, the bottom may soon be carried beyond the reach of at least the coarser kinds of sediment, and marine lime-secreting organisms may afterwards begin to form a calcareous floor beneath the sea. Let us imagine further, that the subsidence ceases for a time, and that by the accumulation of organic remains and partly also by the deposit of fine muddy sediment, the water is shallowed. With this gradual change of depth, the coarser detritus begins once more to be able to stretch seawards, and to overspread the limestones, which, under the altered circumstances, cease to be formed. A gradual silting up of the area takes place, marked by beds of sand and mud, until a renewal of the subsidence, either suddenly or slowly, restores the previous depth and clearness of water, and allows either the old marine organisms, which had been driven off, or their modified descendants to reoccupy the area and build new limestone.

Groups of Strata.—Passing from individual strata to large masses of stratified rock, the geologist finds it needful for convenience of reference to subdivide these into groups. He avails himself of two bases of classification—(1) lithological characters, and (2) organic remains.

1. The subdivision of stratified rocks into groups according to their mineral aspect is an obvious and easily applied classification. Moreover, it often serves to connect together rocks formed continuously in certain circumstances which differed from those under which the strata above and below were laid down—so that it expresses natural and original subdivisions of strata. In the middle of the English Carboniferous system of rocks, for example, a zone of sandy and pebbly beds occurs, known as the Millstone Grit. No abrupt and sharp line can be drawn between these strata and those above and below them. They shade upward and downward into the beds between which they lie. Yet they form a conspicuous belt, traceable for many miles by the scenery to which it gives rise. The red rocks of central England, with their red sandstones, marls, rock-salt, and gypsum, form likewise a well-marked group or rather series of groups. It is obvious, however, that characters of this kind, though sometimes wonderfully persistent over wide tracts of country, must be at best but local. The physical conditions of deposit must always have been limited in extent. A group of strata showing great thickness in one region will be found to die away as it is traced into another. Or its place is gradually taken by another group which, even if geologically contemporaneous, possesses totally different lithological characters. Just as at the present time a group of sandy deposits gradually gives place along the sea-floor to others of mud, and these to others of shells or of gravel, so in former geological periods contemporaneous deposits were not always lithologically

similar. Hence mere resemblance in mineral aspect usually cannot be regarded as satisfactory evidence of contemporaneity except within comparatively contracted areas. The Carboniferous Limestone has already (p. 494) been cited as a notable example. Typically in Belgium, Central England, and Ireland, it is a thick calcareous group of rocks, full of corals, crinoids, and other organisms, which bear witness to the formation of these rocks in the open sea. But traced into the north of England and Scotland, it passes into sandstones and shales, with numerous coal-seams, and only a few thin beds of limestone. The soft clay beneath the city of London is represented in the Alps by hard schists and contorted limestones. We conclude therefore that lithological agreement, when pushed too far, is apt to mislead us, partly because contemporaneous strata often vary greatly in lithological character, and partly because the same lithological characters may appear again and again in different ages. By trusting too implicity to this kind of evidence, we may be led to class together rocks belonging to very different geological periods, and on the other hand to separate groups which really, in spite of their seeming distinction, were formed contemporaneously.

2. It is by the remains of plants and animals imbedded among the stratified rocks that the most satisfactory subdivisions of the geological record can be made, as will be more fully stated in Books V. and VI. A chronological succession of organic forms can be made out among the rocks of the earth's crust. A certain common facies or type of fossils is found to characterize particular groups of rock, and to hold true even though the lithological constitution of the strata should greatly vary. Moreover, though comparatively few species are universally diffused, they possess remarkable persistence over wide areas, and even when they are replaced by others, the same general facies of fossils remains. Hence the stratified formations of two countries geographically distant, and having little or no lithological resemblance to each other, may be compared and paralleled simply by means of their enclosed organic remains.

Order of Superposition—the Foundation of Geological Chronology.—As sedimentary strata were laid down upon one another in a more or less nearly horizontal position, the underlying beds must be older than those which cover them. This simple and obvious truth is termed the law of superposition. It furnishes the means of determining the chronology of rocks, and though other methods of ascertaining this point are employed, they must all be based originally upon the observed order of superposition. The only case where the apparent superposition may be deceptive is where the strata have been inverted, as in the examples cited from the Alps (pp. 314, 518), where the rocks composing huge mountain masses have been so completely overturned that the highest beds appear as if regularly covered by others which ought properly to underlie them. But these are exceptional occurrences, wherein the true order can usually be made out from other sources of evidence.

PART II.—JOINTS.

All rocks are traversed more or less distinctly by vertical or highly inclined divisional planes termed Joints. Soft rocks indeed, such as loose sand and uncompacted clay, do not show these lines; but wherever a mass of clay has been subjected to some pressure and consolidation, it will usually be found to have acquired them more or less distinctly. It is by means of the intersection of joints that rocks can be removed in blocks; the art of quarrying consists in taking advantage of these natural planes of division. Joints differ in character according to the nature of the material which they traverse; those in sedimentary rocks are usually distinct from those in crystalline masses.

1. In Stratified Rocks.—To the presence of joints some of the most familiar features of rock scenery are due (Fig. 217). Joints

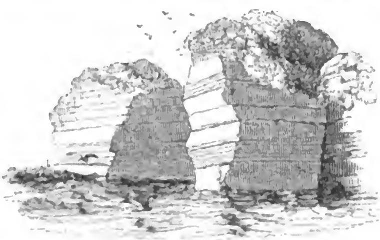


FIG. 217.—CLIFFS CUT INTO RE-ENTERING ANGLES BY LINES OF JOINT (*B.*). (The faces in shadow (*a a*) are one set of joints, those in light (*b b*) another set).

vary in the angles at which they cut the planes of bedding, in the sharpness of their definition, in the regularity of their perpendicular and horizontal course, in their lateral persistence, in number, and in the directions of their intersection. As a rule, they are most sharply defined in proportion to the fineness of grain of the rock. In limestones and close-grained shales, for example, they often occur so clean-cut as to be invisible until revealed by fracture or by the slow disintegrating effects of the weather. The rock splits up along these concealed lines of division whether the agent of demolition be the hammer or frost. In coarse-textured rocks, on the other hand, joints are apt to show themselves as irregular rents along which the rock has been shattered, so that they present an uneven sinuous course, branching off in different directions.

As a rule, they run perpendicular or approximately so to the planes of bedding, and descend vertically at not very unequal distances, so that the portions of rock between them, when seen

in profile, appear marked off into so many wall-like masses. But this symmetry often gives place to a more or less tortuous course with lateral joints in various random directions, more especially where the different strata vary considerably in lithological characters. A single joint may be traced for many yards, sometimes, it is said, for several miles, more particularly when the rock is fine-grained, as in limestone. But where the texture is coarse and unequal, the joints, though abundant, run into each other in such a way that no one in particular can be identified for more than a limited distance. The number of joints in a mass of stratified rock varies within wide limits. Among strata which have undergone little disturbance the joints may be separated from each other by intervals of several yards. But in other cases where terrestrial movement has been considerable, the rocks are so jointed as to have acquired therefrom a fissile character that has nearly or wholly obliterated their tendency to split along the lines of bedding.

An important feature in the joints of stratified rocks is the direction in which they intersect each other. In general they have two dominant trends, one coincident, on the whole, with the direction in which the strata are inclined from the horizon, and the other running transversely at a right angle or nearly so. The former set is known as *dip-joints*, because they run with the *dip* or inclination of the rocks; the latter is termed *strike-joints*, inasmuch as they conform to the *strike* or general outcrop. It is owing to the existence of this double series of joints that ordinary quarrying operations can be carried on. Large quadrangular blocks can be wedged off, which would be shattered if exposed to the risk of blasting. A quarry is usually worked to the dip of a rock; hence the strike-joints form clean-cut faces in front of the workmen as they advance. These are known as "backs," and the dip-joints which traverse them as "cutters." The way in which this double set of joints occurs in a quarry may be seen in Fig. 218, where the close parallel lines traversing the shaded and unshaded faces mark the planes of stratification, which here are inclined from the spectator. The steep faces in light are defined by the strike joints or "backs." The faces in shadow have been quarried out along dip-joints or "cutters." It will be observed that the long face in sunlight is cut by parallel lines of dip-joints not yet opened in quarrying, while in like manner the shaded face of dip-joint is traversed by parallel lines of strike-joint.

Ordinary household coal presents a remarkably well developed system of joints. A block of such coal may be observed to be traversed by fine laminæ, the surfaces of many of which are soft and soil the fingers. These are the planes of stratification. Perpendicular to them run divisional planes, which cut each other at right angles or nearly so, and thus divide the mineral into cubical fragments. One of these sets of joints makes clean sharply defined surfaces, and is known as the *face, slyne, cleat,* or *bord;* the other has rougher, less

regular surfaces, and is known as the *end*. The face remains persistent over wide areas; it serves to define the direction of the roadways in coal-mines, which must run with it.

FIG. 218.—JOINTING IN QUARRY OF CAITHNESS FLAGS, NEAR HOLBURN HEAD.

The cause of jointing has not been satisfactorily explained. According to observations made by Jukes, both strike-joints and dip-joints occur in beds of recently formed coral rock in the Australian and other reefs. These masses of calcareous sediment have certainly never been subject to the pressure of any superincumbent

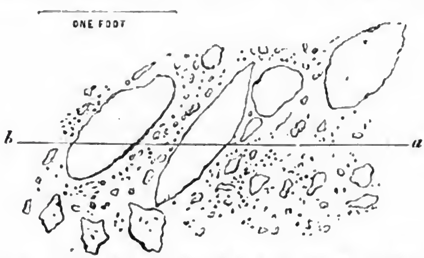


FIG. 219.—PLAN OF COARSE CONGLOMERATE OF BLOCKS OF CAMBRIAN ROCKS IN CARBONIFEROUS LIMESTONE, TRAVERSED BY A LINE JOINT CUTTING THE INDIVIDUAL BOULDERS IN THE LINE *a b*, COAST NEAR SKERRIES, DUBLIN COUNTY (*B.*).

rock. Their joints may possibly be due, as Jukes believed, to contraction during consolidation.[1] But in many cases the existence of joints points to some much more potent cause than mere internal

[1] "Manual of Geology," 3rd Edition, p. 184.

contraction. In some conglomerates, for example, the joints traverse the enclosed pebbles, as well as the surrounding matrix, in such a way that large blocks of hard quartz are cut through by them as sharply as if they had been sliced in a lapidary's machine, and the same joints can be traced continuously through many yards of the rock (Fig. 219).[1] Such instances point to the operation of considerable force.[2] Further indication of movement is often supplied by the rubbed and striated surfaces of joints. These surfaces, termed *slickensides*, have evidently been ground against each other. They are often coated with hæmatite, calcite, chlorite, or other mineral, which has taken a cast of the striæ and then seems itself to be striated.

Joints form natural lines for the passage downward and upward of subterranean water. They likewise furnish an effective lodgment for the action of frost, which wedges off blocks of rock in the manner already described (p. 401). As they serve, in conjunction with bedding, to divide stratified rocks into large quadrangular blocks, their influence in the weathering of these rocks is seen in the symmetrical and architectural as well as splintered, dislocated aspects so familiar in the scenery of sandstone and limestone districts.

Occasionally a prismatic or columnar system of joints may be observed among stratified rocks, particularly in those which have been chemically formed, where, as in the gypsum of the Paris Basin, beds are divided from top to bottom into vertical hexagonal prisms.[3] A columnar structure has often been superinduced upon stratified rocks (sandstone, shale, coal) by contact with intrusive igneous masses (p. 473).

2. **In Massive (Igneous) Rocks.**—While in stratified rocks the divisional planes consist of lines of bedding and of joint, cutting each other usually at a high if not a right angle, in massive igneous rocks they include joints only; and as these do not as a rule present the same parallelism as lines of bedding, unstratified rocks, even though as full of joints, have not the regularity of arrangement of stratified formations. Some massive rocks indeed may have one system of divisional planes so largely developed as to acquire a bedded or fissile character. This structure, characteristically shown by phonolites, may also be detected among ancient porphyries (Fig. 220). Most massive rocks are traversed by two intersecting sets of chief or "master" joints, whereby the rock is divided into long quadrangular, rhomboidal, or even polygonal columns. A third set may usually be noticed cutting across the columns and articulating them into segments, though generally less continuous and dominant than the others (Fig. 221). When these last-named cross-joints are absent or feebly developed, columns many feet in length can be

[1] De la Beche, "Geol. Observer," p. 628.
[2] See an interesting series of experiments by Daubrée (*Comptes Rendus*, lxxxvi. 1878) on the production of faults and joints; *ante*, p. 315.
[3] Jukes, "Manual," 3rd Ed. p. 180.

quarried out entire. Such monoliths have been from early times employed in the construction of obelisks and pillars.

In large masses of granite an outward inclination of the natural divisional planes of the rock may be sometimes observed, as if the granite were really a rudely bedded mass having a dip towards and under the strata which rest upon its flanks. It is not a foliated arrangement of the constituent minerals analogous to the foliation of

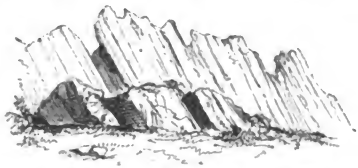


FIG. 220.—PORPHYRY, NEAR CLYNOG VAWR, CAERNARVONSHIRE, DIVIDED INTO SLABS BY A SYSTEM OF CLOSE PARALLEL JOINTS (*B.*).

gneiss, for it can be traced in perfectly amorphous and thoroughly crystalline granite, but is undoubtedly a form of jointing by reason of which the rock weathers into large blocks piled one upon another like a kind of rude cyclopean masonry.[1]

Rocks of finer grain than granite, such as many diorites and dolerites, acquire a prismatic structure from the number and intersection of perpendicular joints. The prisms, however, are unequal in

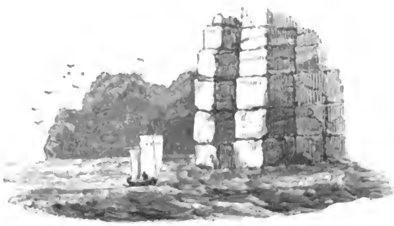


FIG. 221.—JOINTED STRUCTURE OF GRANITE.

dimensions, as well as in the number and proportions of their sides, a frequent diameter being 2 or 3 feet, though they may sometimes be observed three times thicker, and extending up the face of a cliff for 300 or 400 feet. It is by means of joints that precipitous faces of crystalline no less than of sedimentary rock are produced and retained, for they serve as openings into which frost drives every year

[1] In the granite of the axes of the Rocky Mountains and parallel ranges to the westward, a kind of bedded structure has been described as passing under the crystalline schists.

its wedges of ice. They likewise give rise to the formation of the fantastic pinnacles and fretted buttresses characteristic of massive rocks.

As lava, erupted to the surface, cools, and passes into the solid condition, a contraction of its mass takes place. This diminution of bulk is accompanied by the development of divisional planes or joints, more especially diverging from the upper and under surfaces, and intersecting at irregular distances, so as to divide the rock into rude prisms. Occasionally another series of joints, at a right angle to these, traverses the mass, parallel with its upper and under surfaces, and thus the rock acquires a kind of fissile or bedded appearance. The most characteristic structure, however, among volcanic rocks is the prismatic, or, as it is incorrectly termed, "basaltic." Where this arrangement occurs, as it does so commonly in basalt, the mass is divided into tolerably regular pentagonal, hexagonal, or irregularly polygonal prisms or columns, set close together at a right angle to the main cooling surfaces (Figs. 222, 223). These prisms vary from

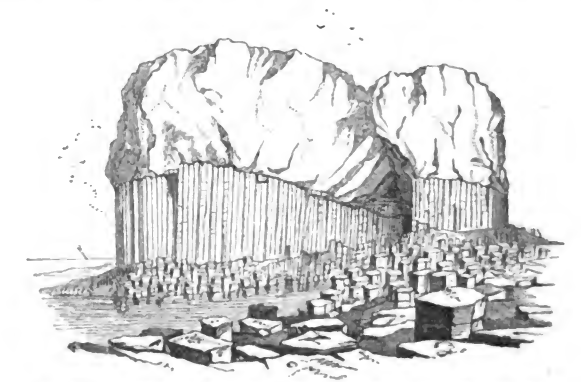


Fig. 222.—Columnar Basalt of Fingal's Cave, Staffa (Macculloch).

2 or 3 to 18 or more inches in diameter, and range up to 100 or even 150 feet in length. Many excellent and well-known examples of columnar structure are exhibited on the coast-cliffs of the Tertiary volcanic region of Antrim and the west of Scotland. In Fig. 222, a lower columnar basalt is overlaid by an upper amorphous or non-columnar bed. In many cases no sharp line can be drawn between such a columnar sheet and the beds above and below, which show no similar structure, but into which the prismatic mass seems to pass.

Considerable discussion has arisen as to the mode in which this

columnar structure has been produced. The experiments of Mr. Gregory Watt were supposed to explain it by the production of a number of spherical concretions in the cooling mass, and the gradual pressure of those soft balls into hexagonal columns, as the mass contracted in cooling. He melted a mass of basalt, and on allowing it to cool observed that, when a small portion was quickly chilled, it took the form of a kind of slag-like glass, not differing much in appearance from obsidian; a larger mass, more slowly cooled, returned to a stony state. He remarked, that during this process small globules make their appearance, which increase in size by the successive formation of external concentric coats, like those of an onion. And he supposed that, as each spheroid must be touched by six others, the whole, if exposed to the same pressure acting in every direction, must be squeezed into a series of hexagons. To account, however, for a long column of basalt, we should have to imagine a pile of balls standing exactly centrically one upon the other, an arrangement which seems hardly possible. The prismatic structure is a species of jointing, due probably to the contraction of the rock as a whole, and not to the production of any internal peculiarities of texture. The concretionary structure associated with the columnar reveals a common tendency to weather out into nodular forms, and may be observed even where the rock is not columnar. As already stated, prismatic forms have been superinduced upon rocks by a high temperature and subsequent cooling, as where coal and sandstone have been invaded by basalt. They may likewise be observed to arise during the consolidation of a substance from aqueous solution. In starch, for example, the columnar structure may be well developed, and not infrequently radiates from certain centres, as in basalt and other igneous rocks.

Mr. Mallet has investigated this subject, and concludes that "all the salient phenomena of the prismatic and jointed structure of basalt can be accounted for upon the admitted laws of cooling, and contraction thereby, of melted rock possessing the known properties of basalt, the essential conditions being a very general homogeneity in the mass cooling, and that the cooling shall take place slowly, principally from one or more of its surfaces."[1] In the more perfectly columnar basalts the columns are sometimes articulated, each prism being separable into vertebræ, with a cup and ball socket at each articulation (Figs. 224 and 225). This peculiarity is traced by Mr. Mallet to the contraction of each prism in its length and in its diameter, and to the consequent production of transverse joints, which, as the resultant of the two contracting strains, are oblique to the sides of the prism, but, as the obliquity lessens towards the centre, assume necessarily, when perfect, a cup-shape, the convex surface pointing in the same direction as that in which the prism has grown. This explanation, however, will hardly account for cases, which are not uncommon, where the convexity points the other way, or where it is

[1] *Proc. Roy. Soc.* January, 1875.

sometimes in one direction sometimes in the other.[1] The remarkable spheroids which appear in many weathered igneous rocks besides basalts, where they are not the result of weathering, may probably be due to some of the conditions under which the original contractions took place. They are quite untraceable on a fresh fracture of the rock. It is only after some exposure to the weather that they begin to appear, and then they gradually crumble away by the successive formation and disappearance of external weathered crusts or coats, which fall off into sand and clay. Almost all augitic or hornblendic rocks, with many granites and porphyries, exhibit the tendency to decompose into rounded spheroidal blocks. The columnar structure, though abundant among modern volcanic rocks, is by no means confined to these. It is as well displayed among the felsites of the Lower Old Red Sandstone, and the basalts of the Carboniferous Limestone in central Scotland, as among the Tertiary lavas of Auvergne or the Vivarais.

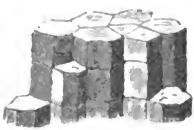


Fig. 223. — Ordinary Columnar Structure of Lava.

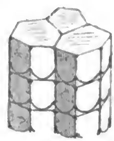


Fig. 224.—Ball-and-Socket Jointing of Columns.

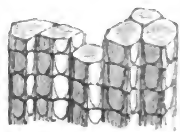


Fig. 225. — Modification of Ball-and-Socket Structure.

3. **In Foliated (Schistose) Rocks.**—The schists likewise possess their joints, which approximate in character to those among the massive igneous rocks, but they are on the whole less distinct and continuous, while their effect in dividing the rocks into oblong masses is considerably modified by the transverse lines of foliation. These lines play somewhat the same part as those of stratification among the stratified rocks, though with less definiteness and precision. The jointing of the more massive foliated rocks, such as the coarser varieties of gneiss, approaches most closely to that of granite; in the finely fissile schists, on the other hand, it is rather linked with that of sedimentary formations. Upon these differences much of the characteristic variety of outline presented by cliffs and crests of foliated rocks depends.

[1] Mr. Scrope pointed this out (*Geol. Mag.* September, 1875), though Mr. Mallet (*Ibid.* November, 1875) replied that in such cases the articulations must be formed just about the dividing surface, between the part of the rock which cooled from above and that which cooled from below.

PART III.—INCLINATION OF ROCKS.

The most casual observation is sufficient to satisfy us that the rocks now visible at the earth's surface are seldom in their original position. We meet with sandstones and conglomerates composed of water-worn particles, yet forming the angular scarps of lofty mountains; shales and clays full of the remains of fresh-water shells and land-plants, yet covered by limestones made up of marine organisms, and these limestones rising into great ranges of hills, or undulating into fertile valleys, and passing under the streets of busy towns. Such facts, now familiar to every reader, and even to many observers who know little or nothing of systematic geology, point unmistakably to the conclusion that the rocks have in many cases been formed under water, sometimes in lakes, more frequently in the sea, and that they have been elevated into land.

But further examination discloses other and not less convincing evidence of movement. Judging from what takes place at the present time on the bottoms of lakes and of the sea, we confidently infer that when the strata now constituting so much of the solid framework of the land were formed, they were laid down nearly horizontally, or at least at low angles (*ante*, p. 477). When, therefore, we find them inclined at all angles, and even standing on end, we conclude that they have been disturbed. Over wide spaces they have been upraised bodily with little alteration of horizontality; but in most places some departure from that original position has been effected.

Dip.—The inclination thus given to rocks is termed their Dip. Its amount is expressed in degrees measured from the plane of the

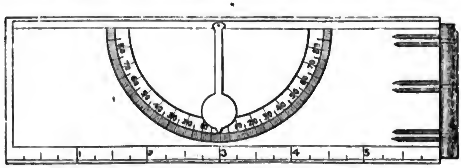


FIG. 226.—CLINOMETER—THE LEAF CONTAINING THE PENDULUM AND INDEX.
(Half the size of the original.)

horizon. Thus a set of rocks half-way between the horizontal and vertical position would be said to dip at an angle of 45°, while if vertical they would be marked with the angle of 90°. The inclination is measured with an instrument termed the Clinometer, which is variously made, but of which one of the simplest forms is shown in Fig. 226. This consists of a thin strip of boxwood, two inches broad, strengthened with brass along the edges, and divided into two leaves, each 6 inches long, hinged together, so that when opened out they form a foot-rule. On the inside of one of these leaves a

graduated arc with a pendulum is inserted. When the instrument is held horizontally, the pendulum points to zero. When placed vertically, it marks 90°. By retiring at a right angle to the direction of dip of a group of inclined beds, and holding the clinometer before the eye until its upper edge coincides with the line of bedding, we readily obtain the amount or angle of dip. In observations of this nature, it is of course necessary either to place the clinometer strictly parallel with the direction of dip, or, if this be impossible, to take two measurements, and calculate from them

Fig. 227.—Apparently Horizontal Strata (*B.*).

the true angle.[1] Simple as observation of dip is, it is attended with some liabilities to error, against which the observer should be on his guard. A single face of rock may not disclose the true dip, especially if it be a clean-cut joint face. In Fig. 227, for example, the strata might be supposed to be horizontal; but another side view

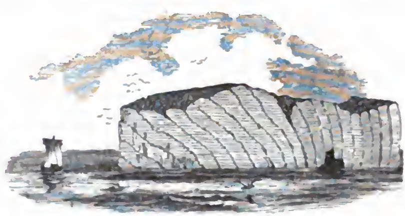


Fig. 228.—Real Inclination of Strata shown in Fig. 227 (*B.*).

of them as (Fig. 228) might show them to be inclined or even vertical.

Again, a deceptive surface inclination is not unfrequently to be seen among thin-bedded strata. Mere gravitation aided by the

[1] In Jukes' "Memoir on the South Staffordshire Coal-Field," in *Memoirs of Geol. Survey* (2nd edit. p. 213), a formula is given for calculating the true dip from the apparent dip seen in a cliff. A graphical method of computing the true dip from observations of two apparent dips has been suggested by Mr. W. H. Dalton, *Geol. Mag.* x. p. 332.

downward pressure of sliding detritus or "soil-cap" suffices to bend over the edges of fissile strata, which, though really dipping into the hill, are thus made to appear superficially to dip away from it (Fig. 229). Similar effects, with even proofs of contortion, may be noticed under boulder clay, or in other situations where the rocks have been bent over and crushed by a mass of ice.

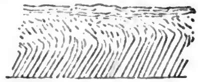


FIG. 229.—DECEPTIVE SUPERFICIAL DIP.

When the dip is outward in every direction from a central point, it is said to be *quâ-quâ-versal* (A in Fig. 231). Strata thus affected are thrown into a dome-shaped structure, while when the dip is towards a central point, they have a basin-shaped structure.

Outcrop.—The edges of strata which appear at the surface of the ground are termed their Outcrop or Basset. If the strata are quite horizontal, the direction of outcrop depends on inequalities of the ground and variations in amount of denudation. Perfectly level ground lying upon horizontal beds shows of course no outcrop, for the surface coincides with the plane of stratification. But occasional water-courses have usually been eroded below the general level, so as to reveal along their sides outcrops of the strata. The remarkable sinuosities of outcrop produced by the unequal erosion of horizontal strata are illustrated in Fig. 230, where A is a map of a piece of ground deeply trenched by valleys, and B that of an area comparatively little denuded. In both cases the outcrops are seen to wind round the sides of the slopes.

Where strata are inclined the course of their outcrop is regulated partly by the direction and amount of inclination, and partly by the form of the ground. When with low angles of dip they *crop out*, that is, rise to the surface, along a perfectly level piece of ground, the outcrop runs at a right angle to the dip. But any inequalities of the surface, such as valleys, ravines, hills, and ridges, will, as in the case of horizontal beds, cause the outcrop to describe a circuitous course, even though the dip should remain perfectly steady all the while. If a line of precipitous gorge should run directly with the dip, the outcrop will there be coincident with the dip. The occurrence of a gently shelving valley in that position will cause the outcrop to descend on one side and to mount in a corresponding way on the other, so as to form a V-shaped indentation in its course. A ridge, on the other hand, will produce a deflection in the opposite direction. Hence a series of parallel ridges and valleys running in the same direction as the dip of the strata underneath causes the outcrop to describe a widely serpentinous course.

The breadth of the outcrop depends on the thickness of the stratum and on the angle of dip. A bed one foot thick inclined at an angle of 1°, on a perfectly level piece of ground would have an outcrop about 60 feet broad. At a dip of 5° the breadth of the outcrop would be a little over 11 feet. At 30° it would be reduced

to 2 feet, and the diminution would continue until, when the bed was on end, the breadth of the outcrop would, of course, exactly correspond with the thickness of the bed. It is further to be observed that among vertical rocks the direction of the outcrop necessarily corresponds with the dip, and continues to do so irrespective altogether of any irregularities of the ground. The lower therefore the angle of inclination the greater is the effect of surface inequalities upon the

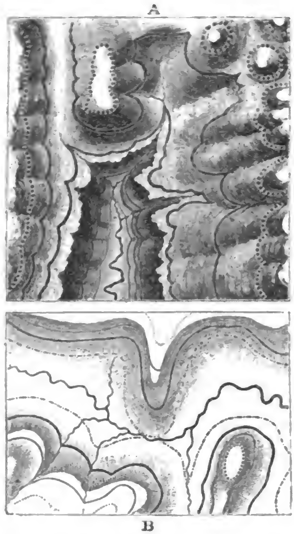


Fig. 230.—Sinuous Outcrops of Horizontal Strata depending on Inequalities of Surface.

The wavy black lines mark the outcrops of successive conformable horizontal beds.

line of outcrop; the higher the angle the less is that influence, till when the beds stand on end it ceases.

Strike.—A line drawn at a right angle to the dip is called the Strike of the rocks. From what has just been said this line must coincide with outcrop when the surface of the ground is quite level as on the beach in Fig. 231, and also when the beds are vertical. At all other times strike and outcrop are not strictly coincident, but the latter wanders to and fro across the former according to changes in the contour of the ground. The strike may be a straight line, or may curve rapidly in every direction, according to the behaviour of the

dip. A set of beds dipping westward for half a mile (*a* to *b* Fig. 231) have a north and south strike for the same distance. If the dip changes to S.W., S., S.E., and E., the strike will bend round in a curving line (as at S). In the case of a *quâ-quâ-versal* dip the strike forms a complete circle (as at A). The dip being ascertained gives the strike, but the strike does not certainly indicate the direction of dip, which may be either to the one side or the other. Two groups of strata dipping the one east and the other west have both a north and south strike. Strike may be conceived as always a level line on the plane of the horizon, so that no matter how much the ground may undulate, or the outcrop may vary, or the dip may change, the strike

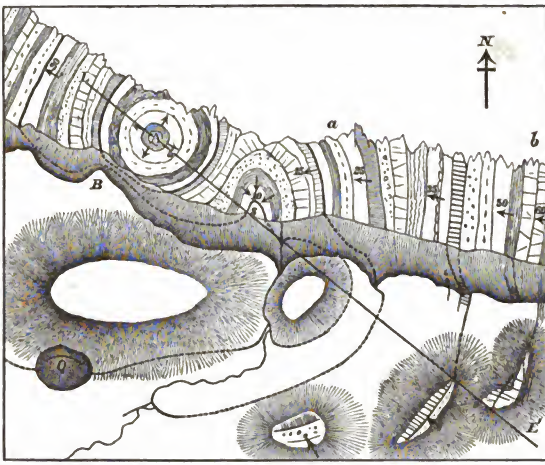


FIG. 231.—GEOLOGICAL MAP, SHOWING STRATA CONTINUOUSLY EXPOSED ALONG A BEACH AND OCCASIONALLY IN THE INTERIOR.

will remain horizontal. Hence in mining operations it is commonly spoken of as the *level-course* or *level-bearing*. A "level" or underground road-way, driven through a coal-seam at right angles to the dip, will undulate in its trend if the dip changes in direction, but it may be made perfectly level, and kept so throughout a whole coal-field so long as it is not interfered with by dislocations.

In Fig. 231, the strike and outcrop are coincident on the flat beach, but cease to be so the moment the ground begins to slope up into the coast-cliff. This is seen in the eastern half of the map, where the lines of outcrop slant up into the cliff at an angle dependent mainly on the amount of the dip. A section drawn in the line L L′ would show the geolgoical structure represented in Fig. 232. By noting the angles of

dip it is possible to estimate the thickness of a series of beds, and how far beneath the surface any given bed might be expected to be found. If, for instance, the horizontal distance across the strike between beds *s* and *a* (Fig. 231) were found to be 200 feet, with a mean dip of 15°, the actual thickness would be 51·8 feet, and bed *a* would be found at a depth of 53·8 feet below the outcrop of *s*. If the same development of strata continues inland, the bed *a* should be found at a little more than 200 feet beneath the surface if a bore were sunk to it in the quarry (Q). If the total depth of rock between *a* and *b* be 1000 feet, then evidently, if the strata could be restored to their original approximately horizontal position, with bed *a* at the surface, bed *b* would be covered to a depth of 1000 feet. It will be noticed also that as the angle of dip increases, the outcrops are thereby brought closer together. Where the outcrops run along the face of a cliff or steep bank (B) they must likewise be drawn together on a map. In reality, of course, these variations may take place though the same vertical thickness of rock everywhere intervenes between the several outcrops.

Fig. 232.—Section along the Line L L' in Fig. 231.

It is usually desirable to estimate the thicknesses of strata, especially where, as in Fig. 231, they are exposed in continuous section. A convenient though not strictly accurate rule for this purpose may be applied in cases where the angle of inclination is less than 45°. The real thickness of a mass of inclined strata may be taken to be $\frac{1}{12}$ of its apparent thickness for every 5° of dip. Thus if a set of beds dips steadily in one direction at 5° for a horizontal space of 1200 feet measured perpendicularly to the strike, their actual thickness will be $\frac{1}{12}$, or 100 feet. If the dip be 15°, the true thickness will be $\frac{3}{12}$, or 300 feet, and so on.[1]

Part IV.—Curvature.

A little reflection will show that though, so far as regards the trifling portions of the rocks visible at the surface, we might regard the inclined surfaces of strata as parts of straight lines, they must nevertheless be parts of large curves. Take for example the section in Fig. 233. At the left hand the strata descend beneath

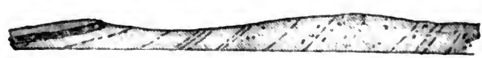


Fig. 233.—Section of Inclined Strata.

the surface at an angle of no more than 15°, but at the opposite end the angle has risen to 60°. There being no dislocation or abrupt

[1] Maclaren's "Geology of Fife and the "Lothians," 2nd Edit. p. xix. For tables for estimating dip and thickness see Jukes' "Manual," p. 748.

change of inclination, it is evident that the beds cannot proceed indefinitely downward at the same angle which they have at the surface, otherwise they would run away from each other, but must bend round to accommodate themselves to the difference of inclination. By prolonging the lines of the beds for some way beneath and above sea-level, we can show graphically that they are necessarily curved (Fig. 234). A section of this kind brings out clearly the additional fact that an upward continuation of the curved beds must have been carried away by the denudation of the surface. In every instance therefore where, in walking over the surface, we traverse a series of strata which gradually, and without dislocations, increase or diminish in inclination, we cross part of a curvature in the strata of the earth's crust. The foldings, however, can often be distinctly seen on cliffs,

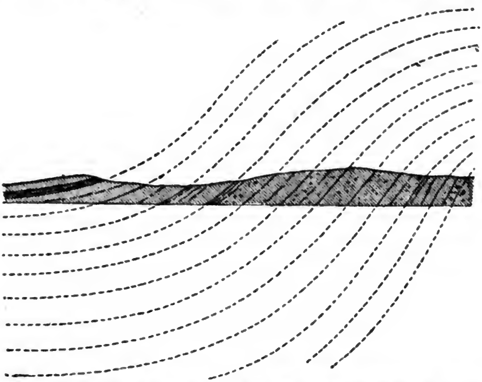


FIG. 234.—SECTION OF INCLINED STRATA, AS IN FIG. 233, SHOWING THAT THEY FORM PART OF A LARGE CURVE.

coast-lines, or other exposures of rock (Fig. 235). The observer cannot long continue his researches in the field without discovering that the strata composing the earth's outer crust have been almost everywhere thrown into curves, usually so broad and gentle as to escape observation except when specially looked for.

If the inclination and curvature of rocks are so closely connected, a corresponding relation must hold between their strike and curvature. In fact, the prevalent strike of a region is determined by the direction of the axes of the great folds into which the rocks have been thrown. If the curves are gentle and inconstant there will be a corresponding variation in the strike. But should the rocks be strongly plicated, there will necessarily be the most thorough coincidence between the strike and the direction of the plication.

Monoclines.—Curvature occasionally shows itself among hori-

zontal or gently inclined strata in the form of an abrupt inclination, and then an immediate resumption of the previous flat or gently sloping character. The strata are thus bent up and continue on the other side of the fold at a higher level. Such bends are called

Fig. 235.—Curved Silurian Rocks on the Coast of Berwickshire.

Monoclines or monoclinal folds, because they present only one fold, or one half of a fold, instead of the two in an arch or trough (Fig. 255, Section 1). The most notable instance of this structure in Britain is that of the Isle of Wight (Fig. 236), where the Cre-

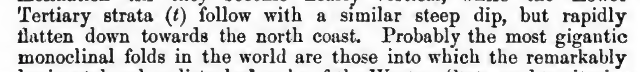


Fig. 236.—Section of a Monoclinal Fold, Isle of Wight.

taceous rocks (c) on the south side of the island rapidly rise in inclination till they become nearly vertical, while the Lower Tertiary strata (t) follow with a similar steep dip, but rapidly flatten down towards the north coast. Probably the most gigantic monoclinal folds in the world are those into which the remarkably horizontal and undisturbed rocks of the Western States and territories of the American Union have been thrown.[1]

From the abundance of inclined strata all over the world we may readily perceive that the normal structure of the visible part of the earth's crust is one of innumerable foldings of the rocks. Sometimes more steeply, sometimes more gently undulated, not infrequently dislocated and displaced, the sedimentary accumulations of former ages everywhere reveal evidence of great internal movement. Here and there the movement has resulted in the formation of a

[1] See Powell's "Exploration of the Colorado River of the West," and "Geology of the Uintah Mountains," in the Reports of the United States Geographical and Geological Survey.

dome-shaped elevation of the strata, wherein, as if pushed up from a single point, they slope away on all sides from the centre of greatest upthrust, with a *quâ-quâ-versal* dip. Where the top of the dome has been removed the successive outcrops of the strata form concentric rings, the lowest at the centre, the highest at the circumference (A in Figs. 231 and 232).

Anticlines and Synclines.—But in the vast majority of cases the folding has taken place, not round a point but along an axis. Where strata dip away from an axis so as to form an arch or saddle, the structure is termed an Anticline, or anticlinal axis (Fig. 237). Where they dip towards an axis,

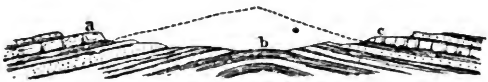


Fig. 237.—Arch, or Anticline, which has been denuded by the Removal of Beds, as shown by the Dotted Line *a c* above the Axis *b*.

forming a trough or basin, it is called a Syncline, or synclinal axis (Fig. 238). An anticlinal or synclinal axis, must always die out unless abruptly terminated by dislocation. In the case of the anticline the axis, after continuing horizontal, or but slightly inclined, at last begins to turn downward, the angle of inclination lessens, and the arch then ends or "noses

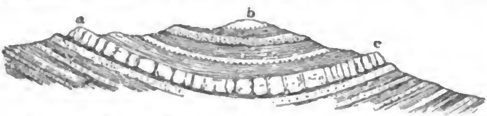


Fig. 238.—Trough, or Syncline, with Strata (*a c*) rising from Each Side of a Central Axis *b*.

out." In a syncline the axis eventually bends upward, and the beds, with gradually lessening angles, swing round it. In a symmetrical anticline or syncline the angle of slope is the same or nearly so on either side (Figs. 237, 238). But a difference of inclination is frequently to be observed. The Appalachian coal-field, for example, as shown by H. D. and W. B. Rogers, presents an instructive series of plications, beginning with symmetrical folds, succeeded by others with steep fronts towards the west, until at last these steeper fronts pass under the opposite sides of the arches, giving rise to a series of inverted folds (Fig. 239).

Fig. 239.—Section across the Folded Rocks of the Appalachian Chain (H. D. Rogers).

Inversion.—Inverted folds occur abundantly in regions of great plication. The Silurian uplands of the south of Scotland, for instance, have the arches and troughs tilted in one direction for miles together, so that in one half of each of them the strata lie bottom upwards (Fig. 240). It is in large mountain-chains, however, that inversion

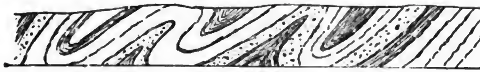


Fig. 240.—Inverted Folds and Isoclinal Structure.

can be seen on the grandest scale. The Alps furnish numerous striking illustrations. On the north side of that chain the Secondary and Tertiary rocks have been so completely turned over for many miles that the lowest beds now form the tops of the hills, while the highest lie deep below them. Individual mountains, such as the Glärnisch and some in the Cantons Glarus and St. Gall (Figs. 241,

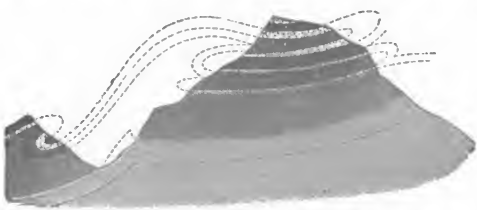


Fig. 241.—Inversion in the Glärnisch Mountain (Baltzer).

242), present stupendous examples of inversion, great groups of strata being folded over and over each other as we might fold carpets. (See p. 314.)

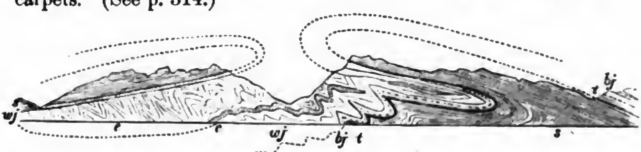


Fig. 242.—Inversion among the Mountains South of the Lake of Wallenstadt, Cantons Glarus and St. Gall (A. von Heim).

e, Eocene; *c*, Cretaceous; *w.j.* White Jura; *b.j.* Brown Jura; *t.* Trias; *s*, schistose rocks, perhaps metamorphosed Palæozoic formations.

Where a series of strata has been so folded and inverted that its reduplicated members appear to dip regularly in one direction, the structure is termed isoclinal. This structure, illustrated on a

small scale among the curved Silurian rocks shown in Fig. 240, occurs on a grand scale among the Alps, where the folds have sometimes been so squeezed together that, when the tops of the arches have been worn away, the strata could scarcely be supposed to have been really inverted, save for the evidence as to their true order of succession supplied by their included fossils. The extent of this compression in the Alps has been already (p. 314) referred to. So intense has been the plication, and so great the subsequent denudation, that portions of Carboniferous strata appear as if regularly interbedded among Jurassic rocks, and indeed could not be separated save after a study of their enclosed organic remains.

A further modification of the folded structure is presented by the fan-shaped arrangement (*structure en éventail*, *Fâcher-Falten*) into

FIG. 243.—FAN-SHAPED STRUCTURE, CENTRAL ALPS.
j', Upper Jurassic Limestone; *j*, Brown Jura and Lias; *t*, Trias; *s*, Schistose rocks.

which highly plicated rocks have been thrown. The most familiar example is that of Mont Blanc, where the sedimentary strata at high angles seem to dip under the crystalline schists (Fig. 243).

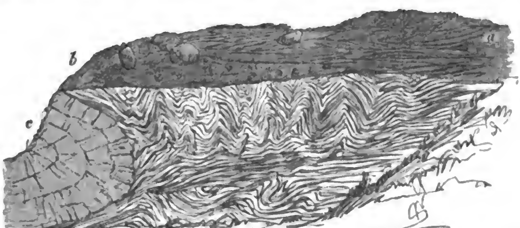


FIG. 244.—LOCALLY CRUMPLED STRATA NEAR A FAULT, DALQUHARRAN, AYRSHIRE.
d, Shales; *c*, Limestone; *b*, Boulder-clay.

Crumpling.—In the general plication of a district there are usually localities where the pressure has been locally so intensified that the strata have been corrugated and crumpled till it becomes almost impossible to follow out any particular bed through the disturbed ground. On a small scale instances of such extreme contortion may now and then be found at faults and landslips, where

fissile shales have been corrugated by subsiding heavy masses of more solid rock (Fig. 244). But it is, of course, among the more plicated parts of mountain-chains that the structure receives its best illustrations. Few travellers who have passed the upper end of the Lake of Lucerne can have failed to notice the remarkable cliffs of contorted rocks near Fluelen. But innumerable examples of equal or even superior grandeur may be observed among the more precipitous valleys of the Swiss Alps. No more impressive testimony could be given to the potency of the force by which

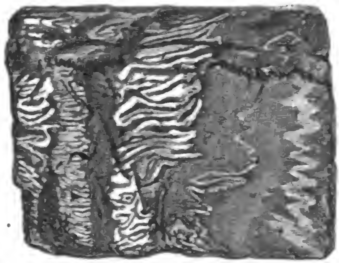


Fig. 245.—Piece of Alpine Limestone, showing fine Puckering produced by Great Lateral Compression.

mountains were upheaved. And yet, striking as are these colossal examples, involving as they do whole mountain masses in their folds, their effect upon the mind is even heightened when we discover that such has been the strain to which solid limestones and other rocks have been subjected that even their minuter layers have been intensely puckered. Some of these minor crumplings are readily visible to the eye in hand-specimens (Figs. 18, 245). But in many foliated crumpled rocks the puckering descends to such extreme minuteness as to be discernible only with the microscope (Fig. 19).

Fig. 246.—Unequal Compression of Coal in Crumpling, Pembrokeshire (*B.*).

It may often be observed that in strata which have been intensely crumpled, the same bed is reduced to the smallest thickness in the arms of the folds, but swells out at the bends as if squeezed laterally into these loops. This appearance, so noticeable on a great scale in mountain structure, may be seen locally among low grounds, as in

Pembrokeshire, where De la Beche has shown that the roofs and pavements of coal-seams are brought together, the coal itself, as having least resistance, being thrust into the loops (Fig. 246).

Deformation.—During the intense compression to which rocks have been subjected their individual particles have been compressed, elongated and fractured, as is instructively shown by the deformation of pebbles and of fossils. These effects have already (p. 311) been referred to.

PART V.—CLEAVAGE.

Cleavage-structure having been described at p. 310, we have to notice here the manner in which it presents itself on the large scale among rock-masses. The direction of cleavage usually remains persistent over considerable regions, and, as was shown by Sedgwick,[1] corresponds, on the whole, with the strike of the rocks. It is, however, independent of bedding. Among curved rocks the cleavage planes may be seen traversing the plications without sensible deflection from their normal direction, parallelism, and high angle. But their

FIG. 247.—CURVED AND CONTORTED DEVONIAN ROCKS, NEAR ILFRACOMBE (*B.*). Bedding and cleavage planes are coincident at *a* and *c*, but nearly at right angles at *b*.

general coincidence with the axes of plications serves to indicate a community of origin for cleavage and folding, as results of the lateral compression of rocks. Among curved strata the planes of cleavage sometimes coincide with and are sometimes at right angles to the planes of bedding, according to the angles of the folding (Fig. 247). The persistence of cleavage planes across even the most diverse kinds of rock, both sedimentary and igneous, was first described by Sedgwick. Jukes also pointed out that over the whole of the south of Ireland the trend of the cleavage seldom departs 10° from the normal direction E. 25° N., no matter what may be the differences in character and age of the rocks which it crosses. But though cleavage is so persistent, it is not equally well developed in every kind of rock. As already explained (p. 311), it is most perfect in fine-grained argillaceous rocks, which have been altered by it into slates, and may be observed at once to change its character as it passes from such rocks into others of a more granular or gritty texture. Occasional traces of distortion or deviation of the cleavage planes may be observed at the contact of two dissimilar kinds of rock (Fig. 248).

[1] "On the Structure of Large Mineral Masses," *Trans. Geol. Soc.* 2nd Ser. III.—an admirable memoir, in which the structure of a great cleavage region is clearly and graphically described.

A region may have been subjected at successive intervals to the compression that has produced cleavage. The Silurian rocks of the south-west of Ireland were upturned and probably cleaved before

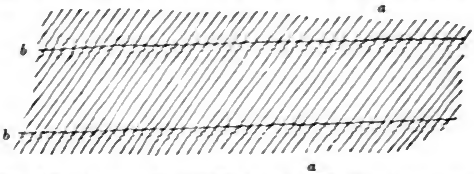


Fig. 248.—Cleaved Strata, Wiveliscombe, West Somerset (*B.*).
Showing the cleavage lines *a a* slightly undulating at the partings of the strata *b b*.

the deposition of the Old Red Sandstone, which has in turn been well cleaved.[1] Evidence of the relative date of cleavage may be obtained from unconformable junctions and from conglomerates. An uncleaved series of strata, lying upon the denuded edges of an older cleaved series, proves the date of cleavage to be intermediate between the periods of the two groups. Fragments of cleaved rocks

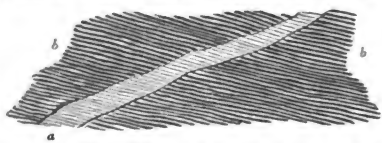


Fig. 249.—Vein of Porphyry (*a*) Crossing Devonian Slates (*b*), Plymouth Sound, both being traversed by Cleavage (*B.*).

in an uncleaved conglomerate show that the rocks whence they were derived had already suffered cleavage before the detritus forming the conglomerate was removed from them. An intrusive igneous rock, traversed with cleavage planes like its surrounding mass, points to cleavage subsequent to its intrusion (Fig. 249).[2]

Part VI.—Dislocation.

The movements which the crust of the earth has undergone have not only folded and corrugated the rocks, but have fractured them in all directions. These dislocations may be either simple **Fissures**, that is, rents without any vertical displacement of the mass on either side, or **Faults**, that is, rents where one side has been pushed up or has sunk down. It is not always possible in a shattered rock to discriminate between joints and fissures which seem there to be both the simultaneous effects of the same cause,

[1] De la Beche, "Geol. Obs." p. 620. [2] De la Beche, *op. cit.* p. 621.

the fissures being merely enlarged joints. It is common to meet with traces of friction along the walls of fissures, even when no proof of actual vertical displacement can be gleaned. The rock is then often more or less shattered on either side, and the contiguous faces present rubbed and polished or "slickensided" surfaces. Mineral deposits may also commonly be observed encrusting the cheeks of a fissure, or filling up, together with broken fragments of rock, the space between the two walls. The structure of mineral veins in fissures is described in Part IX.

In a large proportion of cases, however, there has been not only

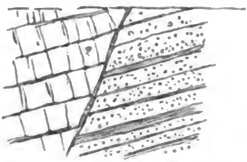


FIG. 250.—SECTION OF SHARPLY-DEFINED FAULT WITHOUT CONTORTION OF THE ROCKS.

fracture but displacement. The rents have become faults as well as fissures. Faults on a small scale are sometimes sharply-defined lines, as if the rocks had been sliced through and fitted together again after being shifted. In such cases, however, the harder portions of the dislocated rocks will usually be found slickensided. More frequently some disturbance has occurred on one or both sides of the fault (Fig. 251). Sometimes in a series of strata the beds on

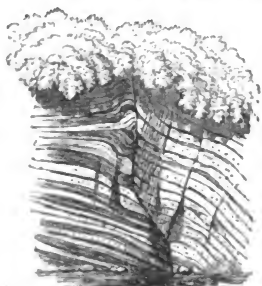


FIG. 251.—SECTION OF A FAULT, SHOWING DISTURBANCE OF ROCKS.

the side which has been pushed up are bent down against the fault, while those on the opposite side are bent up (Fig. 252). Most commonly the rocks on both sides are considerably broken, jumbled, and crumpled, so that the line of fracture is marked by a belt or

wall-like mass of fragmentary rock, known as "fault-rock." Where a dislocation has occurred through materials of very unequal hardness, such as solid limestone bands and soft shales, or where its course has been undulating, the relative shifting of the two sides has occasionally brought opposite prominences together so as to leave wider interspaces (Fig. 301). The actual breadth of a fault may vary from a mere chink into which the point of a knife could hardly be inserted, up to a band of broken and often consolidated materials many yards

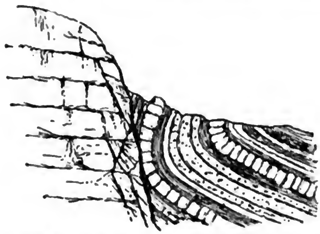


Fig. 252.—Section of Fault with Inverted Beds on the Down-throw Side.

wide. Where a fault has a considerable throw it is sometimes flanked by parallel small faults. The occurrence of these close together will obviously produce the appearance of a broad zone of much fractured rock along the trend of a main fissure. A line of disturbance may consist of several parallel faults of nearly equal magnitude (Fig. 255, Section 3).

Inclination of Faults.—Faults are sometimes vertical, but are generally inclined. The largest faults, that is, those which have the greatest vertical displacement, slope at high angles, while those

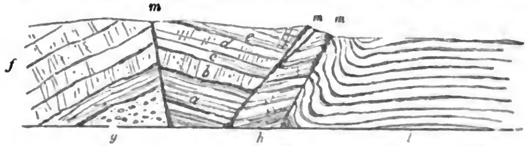


Fig. 253.—Section of Group of Faults, Coast of Glamorganshire, West of Lavernock Point (*B.*).

m m m, three adjacent faults by which the inclination of the strata is shifted and some of the beds are crumpled; *a*, dolomitic limestone and marl; *b*, *c*, *d*, *e*, *f*, dolomitic limestone; *g*, dolomitic conglomerate; *h*, beds corresponding with those on the left; *l*, Lias, thrown in by a "reversed" fault.

of only a few feet or yards may be inclined as low as 18° or 20°. The inclination of a fault from the vertical is called its *hade*. In Fig. 254, for example, the fault at B, being vertical, has no hade, but that at A hades at an angle of 70° from the vertical to the left hand.

The amount of displacement is represented as the same in both instances, so that the level of the beds is raised between the two faults above the uniform horizon which it retains beyond them.

The effect of the inclination of faults is to give the appearance of lateral displacement. In Fig. 254, for example, where the hade of one fault is considerable, the two severed ends (*c* and *d*) of the black bed appear to have been pulled asunder. The horizontal distance to which they are removed does not depend upon the amount of vertical displacement, but upon the angle of hade. A small fault with a great hade will shift strata laterally much more than a large fault with a small hade. It is obvious that the angle of hade must seriously affect the value of a coal-field. If the black bed in the same figure be supposed to be a coal-seam, it could be worked from either side up to *c* and *d*, but there would be a space of barren ground between these two points, where the seam never could be found. The lower the angle of hade the greater the breadth of such barren ground. Hence the more nearly vertical the lines of fault, the better for coal-fields.

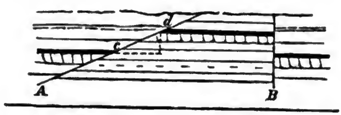


FIG. 254.—SECTION OF INCLINED AND VERTICAL FAULTS.

In the vast majority of cases faults hade in the direction of downthrow, in other words, they slope away from the side which has risen. The explanation of this structure is doubtless to be found in the fact that the portion of the terrestrial crust towards which a fault hades presents a less area of base to pressure from below, and has thus a smaller support than the mass with the broad base on the opposite side. The mere inspection of a fault in any natural or artificial section suffices, in most cases, to show which is the upthrow side. In mining operations the knowledge of this rule is invaluable, for it decides whether a coal-seam, dislocated by a fault, is to be sought for by going up or down. In Fig. 254, a miner working from the left, and meeting with the fault at *c*, would know from its hading towards him that he must ascend to find the coal. On the other hand, were he to work from the right, and catch the fault at *d*, he would see that it would be necessary to descend. According to this rule, a normal fault never brings one part of a bed below another part, so as to be capable of being pierced twice by the same vertical shaft. Exceptional cases, however, or "reversed faults," where the hade is reversed, do occasionally appear, especially in regions where the rocks have been excessively plicated, and where one half of a fold has been pushed over another (Figs. 253 and 255, section 4).

Connection between Faults and Folds.—A monoclinal fold may by increase of movement be developed into a fault (Fig. 255). Beautiful examples of this relation have been observed by Powell and others among the little disturbed formations of the great plateaux of Utah and Wyoming. Other illustrations have been adduced by Heim from the more plicated rocks of the Alps.[1]

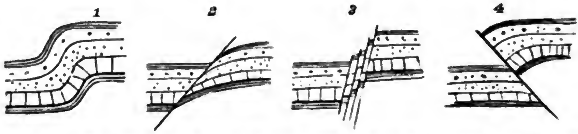


Fig. 255.—Sections to show the relations of Monoclinal Folds and Faults.

1, Monoclinal fold; 2, Monoclinal fold replaced by a single fracture; 3, Monoclinal fold converted into a series of parallel fractures; 4, Monoclinal fold developed by increase of plication into a reversed fault.

Throw of Faults.—That faults are vertical displacements of parts of the earth's crust is most clearly shown when they traverse stratified rocks, for the regular lines of bedding and the originally flat position of these rocks afford a measure of the disturbance. In Fig. 254 the same series of strata occur, on either side of each of the two faults, and the same stratum can be recognized, so that measurement of the amount of displacement is here obviously simple. The measurement is made from the truncated end of any given stratum vertically to the level of the opposite end of the same stratum on the other side of the fault. Where the fault is vertical, like that to the right in Fig. 254, the mere distance of the fractured ends from each other is the amount of displacement. In an inclined fault the level of the selected stratum is protracted across the fissure until a vertical from it will reach the level of the same bed, as shown by the dotted lines. The length of this vertical is the amount of vertical displacement, or the *throw* of the fault.

Unless beds the horizons of which are known can be recognized on both sides of a fault, exposed in a cliff or other section, the fault at that particular place does not reveal the extent of its displacement. It would not, in such a case, be safe to pronounce the fault to be large or small in the amount of its throw, unless we had other evidence from which to infer the geological horizon of the beds on either side. A fault with a considerable amount of displacement may make little show in a cliff, while, on the other hand, one which, to judge from the jumbled and fractured ends of the beds on either side, might be supposed to be a powerful dislocation, may be found to be of comparatively slight importance. Thus, on the cliff near Stonehaven, in Kincardineshire, one of the most notable faults in Great Britain runs out to sea, between the ancient crystalline rocks of the Highlands

[1] See Powell in the works cited already on p. 516. Heim, *Mechanismus der Gebirgsbildung*, Plate xv., Fig. 14.

and the Old Red sandstones and conglomerates of the Lowlands of Scotland. So powerful have been its effects that the strata on the Lowland side have been thrown on end for a distance of two miles back from the line of fracture, so as to stand upright along the coast-cliffs, like books on a library shelf. Yet at the actual point where the fault reaches the sea and is cut in section by the shore-cliff, it does not appear as a line of shattered rock. On the contrary, no one, placed at once upon the spot, would be likely to suspect the existence of a fault at all. The red sandstone and the reddened Highland slates have been so compressed and, as it were, welded into each other, that some care is required to trace the demarcation between them.

Variations in the Effects of Faults.—The same fault may give rise to very different effects, according to variations in the inclination or curvature of the rocks which it traverses, or to the influence of branch faults diverging from it. Faults among inclined strata may, in most districts, be conveniently grouped into two series, one running in the same general direction as the dip of the strata, the other approximating to the trend of the strike. They are accordingly classified as *dip-faults* and *strike-faults*, which, however, are not always to be sharply marked off from each other, for the dip-faults will often be observed to deviate considerably from the normal direction of dip, and the strike-faults from the prevalent strike, so that in such cases they pass into each other.

A dip-fault produces at the surface the effect of a lateral shift of the strata. This effect increases in proportion as the angle of dip lessens, but ceases altogether when the beds are vertical. Fig. 256

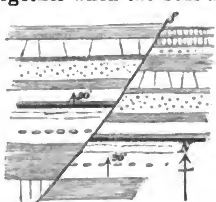


FIG. 256.—PLAN OF STRATA CUT BY A DIP-FAULT.

may be taken as a plan of a dip-fault (*f f*) traversing a series of strata which dip northwards at 20°. The beds on the east side look as if they had been pushed horizontally southwards. That this apparent horizontal displacement is due really to a vertical movement, and to the subsequent planing down of the surface by denuding agents, will be clear, if we consider what must be the effect of the vertical ascent or descent of the inclined beds on one side of a dislocation. The part on one side of the fracture is pushed up, or, what is equivalent, that on the other side is let down. If the strike

of the beds be supposed to be east and west, then a horizontal plane cutting the dislocated strata will show the portion on the west or upthrow side of the fault lying to the north of that on the east or downthrow side. The effect of denudation has usually been practically to produce such a plane, and thus to exhibit an apparently lateral shift. This surface displacement has been termed the *heave* of a fault. Its dependence upon the angle of dip of the strata may be seen by a comparison of Sections A and B in Fig. 257.

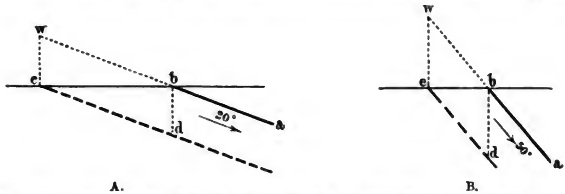


Fig. 257.—Sections to show the Variation of Horizontal Displacement or Heave of Faults, according to the Angle of Inclination of Strata.

In the former, the bed *a b*, which may be supposed to be one of those in Fig. 256, dipping north, at 20°, once prolonged above the present surface (marked by the horizontal line), is represented as having dropped from *w b* to *c d*. The heave amounts to the horizontal distance between *c* and *b*, the throw being the vertical distance between *b* and *d*. But if the angle should rise to 50°, as in B, though the amount of throw or vertical displacement is there one-fourth greater, the heave or horizontal shift diminishes to less than a half of what it is in A. This diminution will continue with every increase of inclination in the strata till among vertical beds there can be no heave at all.

Strike-faults, where they exactly coincide with the strike, may

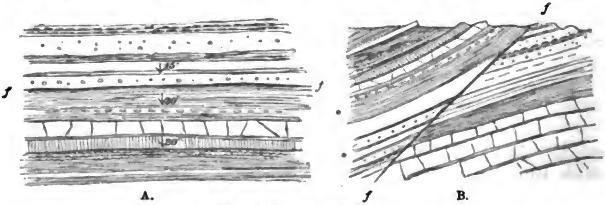


Fig. 258.—Strike-Fault.

A, Plan; B, Section across the plan in the line of the arrows.

remove the outcrop of some strata by never allowing them to reach the surface. Fig. 258 shows a plan (A) and section (B) of one of these faults *f f*, having a downthrow towards the direction of dip. In crossing the strike we pass successively over the edges

of all the beds, except the part between the asterisks, which is cut out by the fault as shown in the section. It seldom happens, however, that such strict coincidence between faults and strike continues for more than a short distance. The direction of dip is apt to vary a little even among comparatively undisturbed strata, every such variation causing the strike to undulate and thus to be cut more or less obliquely by the line of dislocation, which may nevertheless run quite straight. Moreover, any increase or diminution in the throw of a strike-fault will, of course, have the effect of bringing the dislocated ends of the beds against the line of dislocation. In Fig. 259, for instance, which represents in plan another strike-fault (*f*), we see that the amount of throw increases towards the right so as to allow lower beds successively to appear on one side, while towards the left it diminishes, and finally dies out in bed Y.

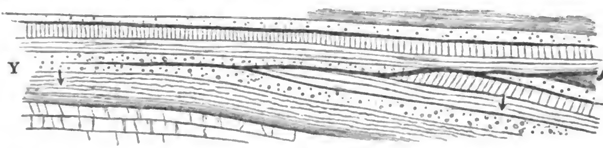


FIG. 259.—PLAN OF STRATA TRAVERSED BY A DIMINISHING STRIKE-FAULT.

Their effects become more complicated where faults traverse undulating and contorted strata. The connection between folding and fracture has already been adverted to in the case of monoclinal bends. It sometimes happens that the plications are subsequently fractured so that the fault may appear to be alternately a downthrow on opposite sides, according to the position of the arches and troughs which it crosses. This structure may be illustrated by a plan and sections of a dislocated anticline and syncline, which will also show clearly how the apparently lateral displacement of outcrop produced by dip-faults is due to vertical movement. Fig. 260 represents a plan of strata thrown into an anticlinal fold AA and a synclinal fold SS, and traversed by a fault FF, having an upthrow (*u u*) to the east. A dip-fault shifts the outcrop towards the dip on the upthrow side, and this will be observed to be the case here. On the west side of the fault, the black bed *a*, dipping towards the south, is truncated by the fault at *u*, and the portion on the upthrow side is shifted forwards or southward. Crossing the syncline we meet with the same bed rising with a contrary dip, and as the upthrow of the fault still continues on the same side the portion of the bed on the west side of the fault must be sought further south. The effect of the fault on the syncline is to widen the distance between the two opposite outcrops of a bed on the downthrow side, or to narrow it on the upthrow side. On the southern slope of the anticline A the same bed once more appears, and again is shifted

forwards as before on the upthrow side. Hence in an anticline, the reverse effect takes place, for there the space between the two outcrops is narrowed on the downthrow side. A section along the east or upcast side of the fault would give the structure represented

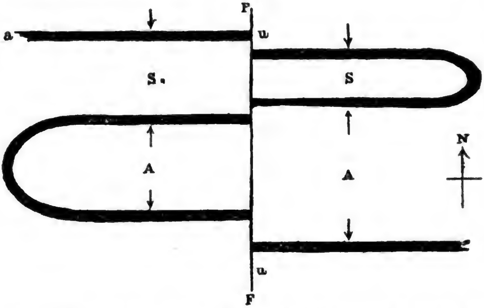


Fig. 260.—Plan of Anticline (A) and Syncline (S), dislocated by a Fault (F F).

in Fig. 261 (1); while one along the downcast side would be as in (2). These two sections clearly prove that the shifting of the outcrops at the surface can be simply explained by a mere vertical movement.

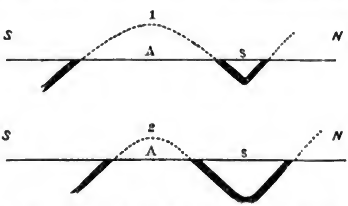


Fig. 261.—Sections along the Fault in Fig. 260.
1, Section along the upcast side; 2, Section along the downthrow side.

Dying out of Faults.—Dislocation may take place either by a single fault or as the combined effects of two or more. Where there is only one fault, one of its sides may be pushed up or let down, or there may be a simultaneous opposite movement on either side. In such cases, there must be a gradual dying out of the dislocation towards either end; and there will usually be one or more points where the displacement has reached a maximum. Sometimes, as may be seen in coal-workings, a fault with a considerable maximum throw splits into minor faults at the terminations. In other cases the offshoots take place along the line of the main

fissure. Exceedingly complicated examples occur in some coal-fields, where the connected faults become so numerous that no one of them deserves to be called the main or leading dislocation. By a series of branch faults the effect of a main fault may be neutralized or reversed. Suppose, for example, that a main fault at its eastern portion throws down 60 fathoms to the north, and that at intervals three faults on the same side strike off from it, each having a down-throw of 25 fathoms to the east; the combined effect of these branch faults will be to reverse the throw of the main fault towards its western end, and make it a downthrow of 15 fathoms to the south.

Groups of Faults.—The subsidence or elevation of a large mass or block of rock has usually taken place by a combination of faults. Detailed maps of coal-fields, such as those published by the Geological Survey of Great Britain on a scale of six inches to a mile, furnish much instructive material for the study of the way in which the crust of the earth has been reticulated by faults. In most

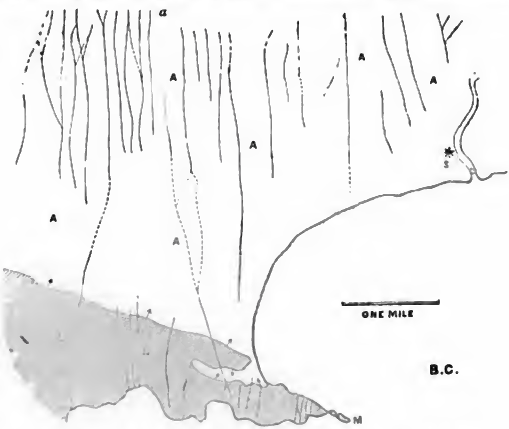


FIG. 262.—MAP OF PART OF THE SOUTH WALES COAL-FIELD.

A A, Coal measures; L L, Carboniferous limestone dipping beneath the coal-measures as shown by the arrows; *a a*, dip-faults; S, Swansea; M, the Mumbles; B. C. Bristol Channel.

cases, dip-faults are predominant, sometimes to a remarkable extent, as in the portion of the South Wales coal-field represented in Fig. 262. In other places the dislocations run in all directions so as to divide the ground into an irregular network.

It often happens that, by a succession of parallel and adjoining faults, a series of strata is so dislocated that a given stratum which may be near the surface on one side is carried down by a series of

steps to some distance below. Excellent examples of these step-faults (Fig. 263) are to be seen in the coal-fields on both sides of the upper part of the estuary of the Forth. Instead, however, of

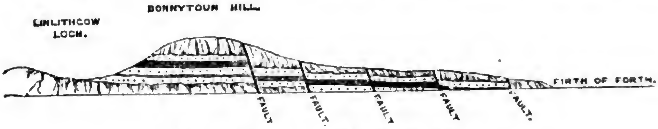


Fig. 263.—Step-Faults, Linlithgowshire.

having the same downthrow, parallel faults frequently show a movement in opposite directions. If the mass of rock between them has subsided relatively to the surrounding ground, they are trough-faults (Fig. 264). They enclose wedge-shaped masses, of which the apices, formed by the junction of two faults, point downwards. It will be observed that the hade of these faults is in each case towards the downthrow side, and that the wedge-shaped masses with broad bottoms have risen, while those with narrow bottoms and broad tops have sunk.

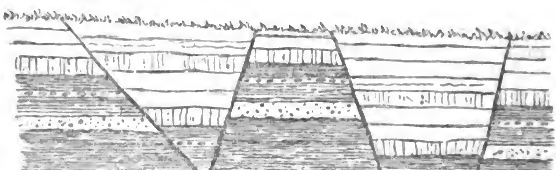


Fig. 264.—Trough-Faults.

Detection and tracing of Faults.—As a rule, faults give rise to little or no feature at the surface, so that their existence would commonly not be suspected. They comparatively rarely appear in visible sections, but are apt rather to conceal themselves under surface accumulations just at those points in a ravine or other natural section where we might hope to catch them. Yet they undoubtedly constitute one of the most important features in the geological structure of a district or country, and should consequently be traced with the greatest care. In the majority of cases, in countries like much of central and northern Europe, where the ground is covered with superficial deposits, the position of faults cannot be seen, but must be inferred. Experience will teach the student that the mere visible section of a fault on some cliff or shore does not necessarily afford such clear evidence of its nature and effects as may be obtained from other parts of the region where it does not show itself at the surface at all. In fact, he might be deceived by a single section with a fault exposed in it, and might be

led to regard that fault as an important and dominant one, while it might be only a secondary dislocation in the near neighbourhood of a great fracture, for which the evidence would be elsewhere obtainable, but which might never be seen itself. The actual position (within a few yards) of a large fault, its line across the country, its effect on the surface, its influence on geological structure, its amount of vertical displacement at different parts of its course—all this information may be admirably worked out, and yet the actual fracture may never be seen in any one single section on the ground. A visible exposure of the fracture would be interesting; it would give the exact position of the line at that particular place; but it would not be necessary to prove the existence of the fault, nor would it perhaps furnish any additional information of importance. The existence of an unseen fault may usually be determined by an

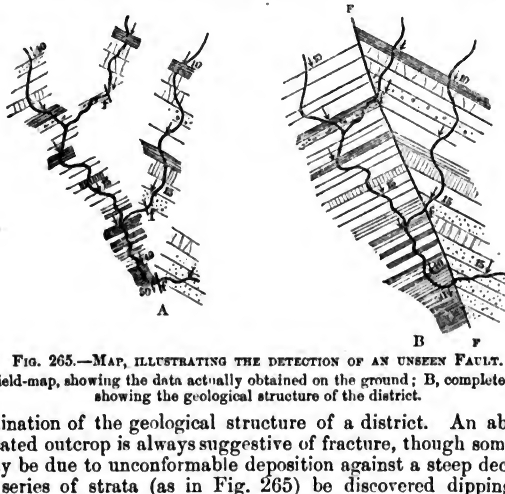


FIG. 265.—MAP, ILLUSTRATING THE DETECTION OF AN UNSEEN FAULT.
A, Field-map, showing the data actually obtained on the ground; B, completed Map, showing the geological structure of the district.

examination of the geological structure of a district. An abruptly truncated outcrop is always suggestive of fracture, though sometimes it may be due to unconformable deposition against a steep declivity. If a series of strata (as in Fig. 265) be discovered dipping continuously in one general direction at angles of 10° or more, and if at a short distance another different group be found inclined in another direction, the two series thus striking at each other, a fault will almost always be required to explain their relation. If all the evidence obtainable, from the sections in water-courses or otherwise, be put upon a map (as in A, Fig. 265) it will be seen that a dislocation must run somewhere near the points marked *f f*, as there is no room for either series to turn round so as to dip below the other. They must be mutually truncated. The completed map would represent them separated by a fault (FF, in

Fig. B). The upthrow or downcast side of the dislocation would be determined by the observer's knowledge of the order of superposition of the respective groups of strata.

The existence of a fault having been thus proved from an examination of the geological structure of the ground, its line across the country may be approximately laid down—1st, by getting exposures of the two sets of rock, or the two ends of a severed outcrop on either side, as near as possible to each other, and tracing the trend of the dislocation between; 2nd, by noting lines of springs along the supposed course of the fault, subterranean water frequently finding its way to the surface along such fissures; 3rd, by attending to surface features, such as lines of hollow, or of ridge rising above hollow, the effect of a fault often being to bring rocks of unequal resistance together so as to allow the more durable to rise more or less steeply from the fracture.[1]

Part VII.—Eruptive (Igneous) Rocks as Part of the Structure of the Earth's Crust.

The lithological differences of eruptive rocks having already been described in Book II. (p. 129), it is their larger features in the field that now require attention,—features which in some cases are readily explicable by the action of modern volcanoes; in other cases bring before us parts of the economy of volcanoes never observable in any recent cone; or reveal deep-seated rock-structures which lie far beneath the upper or volcanic zone of the terrestrial crust. A study of the igneous rocks of former ages as built up into the framework of the crust, serves to augment our knowledge of volcanic action.

At the outset, it is evident that if eruptive rocks have been

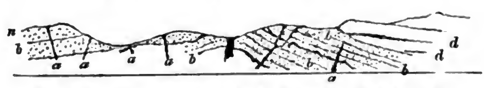


Fig. 266.—Extensively-denuded Volcanic District (*B.*).

extruded from below in all geological ages, and if at the same time denudation of the land has been continuously in progress, many masses of molten material poured out at the surface must have been removed. But the removal of these superficial sheets must necessarily have uncovered their roots or downward prolongations, and the greater the denudation the deeper down must have been the original position of the rocks now exposed to daylight. In Fig. 266, for example, a section by De la Beche shows a district in which a series of tuffs and breccias (*b b*) traversed by dykes (*a a*) is covered unconformably by a newer series of deposits (*d d*). Properly to appreciate the relations and history of the rocks, we must bear in mind

[1] See "Field Geology," by the author, Chapter X.

that originally they presented some such outline as in Fig. 267, where the present surface (that of Fig. 266) down to which denudation has

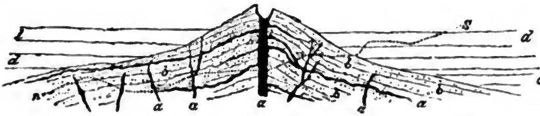


FIG. 267.—RESTORED OUTLINE OF THE ORIGINAL FORM OF GROUND IN FIG. 266 (*B.*).

proceeded is represented by the dotted line *n s.*[1] We may therefore *à priori* expect to encounter different levels of eruptivity, some rocks being portions of sheets that solidified at the surface, others forming different parts of the pipe or column that connected the superficial sheets with the internal reservoir whence the lava proceeded. But we may also infer that many masses of molten rock, after being driven so far upward, came to rest without ever finding their way to the surface. It cannot always be affirmed that a given mass of intrusive igneous rock, now denuded and exposed at the surface, was ever connected with any superficial manifestation of volcanic action.

Now there will obviously be some difference between the superficial and the deep-seated masses, and this difference is of so much importance in the interpretation of the history of volcanic action that it ought to be clearly kept in view. It would manifestly lead to confusion if no distinction were drawn between those igneous masses which reached the surface and consolidated there, like modern lava-streams or showers of ashes, and those which never found their way to the surface but consolidated at a greater or less depth beneath it. There must be the same division to be drawn in the case of every active volcano of the present day. But at a modern volcano only the materials which reach the surface can be examined, the nature and arrangement of what still lies underneath being matter of inference. In the revolutions to which the crust of the earth has been subjected, however, denudation has, on the one hand, removed superficial sheets of lava and tuff, and has exposed the subterranean continuations of the erupted rocks; and, on the other hand, has laid open the very heart of masses which, though eruptive, seem never to have been directly connected with actual volcanic outbursts. All those subterranean intruded masses, now revealed at the surface only after the removal of a depth of overlying rock, may be grouped together into one division under the names Plutonic, Intrusive, or Subsequent. On the other hand, all those which came up to the surface as ordinary volcanic rocks, whether molten or fragmental, and were consequently contemporaneously interstratified with the formations which happened to be in progress on the surface at the time, may be classed in a second group under the names Volcanic, Interbedded, or Contemporaneous.

[1] De la Beche, "Geol. Observer," p. 561.

It is obvious that these can be used only as relative terms. Every truly volcanic mass which, by being poured out as a lava-stream at the surface, came to be regularly interstratified with contemporaneous accumulations, must have been directly connected below with molten matter which did not reach the surface. One part of the total mass therefore would be included in the second group, while another portion, if ever exposed by geological revolutions, would be classed with the first group. Seldom, however, can the same masses which flowed out at the surface be traced directly to their original underground prolongations.

It is evident that an intrusive rock, though necessarily subsequent in age to the rocks through which it has been thrust, need not be long subsequent. Its relative date can only be certainly affirmed with reference to the rocks through which it has broken. It must obviously be younger than these, even though they lie upon it, if they bear evidence of alteration by its influence. The probable geological date of its eruption must be decided by evidence to be obtained from the grouping of the rocks all around. Its intrusive character can only certainly determine the limit of its antiquity. We know that it must be younger than the rocks it has invaded; how much younger must be otherwise determined. Thus, a mass of granite or a series of granite veins (*a a*, Fig. 268) is manifestly

Fig. 268.—Section showing the Relative Age of an Intrusive Rock (*B.*).

posterior in date to the rocks (*b b*) through which it has risen. But it must be regarded as older than overlying undisturbed and unaltered rocks (*c*), or than others lying at some distance (*e f*) which contain worn fragments derived from the granite.

On the other hand, an interbedded or contemporaneous igneous rock has its date precisely fixed by the geological horizon on which it lies. Sheets of lava or tuff interposed between strata in which such fossils as *Calymene Blumenbachii*, *Leptæna sericea*, *Atrypa reticularis*, *Orthis elegantula*, and *Pentamerus Knightii* occur, would be unhesitatingly assigned by a geologist to submarine volcanic eruptions of Upper Silurian age. A lava-bed or tuff intercalated among strata containing *Sphenopteris affinis*, *Lepidodendron Veltheimianum*, *Leperditia*, and other associated fossils, would unequivocally prove the existence of volcanic action at the surface during the Lower Carboniferous period, and at that particular part of the period represented by the horizon of the volcanic bed. Similar eruptive material associated with *Ammonites*, *Belemnites*, *Pentacrinites*, &c., would certainly belong to some zone in the great Mesozoic suite of formations. An interbedded and an intrusive mass found on the same platform of strata need not necessarily be coeval. On the contrary, the latter, if clearly intruded along the horizon of the

former, would obviously be posterior in date. It will be understood then that the two groups have their respective limits determined mainly by their relations to the rocks among which they may happen to lie, though there are also special internal characters which help to discriminate them.

The value of this classification for geological purposes is great. It enables the geologist to place and consider by themselves the granites, quartz-porphyries, and other crystalline masses which, though lying sometimes perhaps at the roots of ancient volcanoes, and therefore intimately connected with volcanic action, yet owe their special characters to their having consolidated under pressure at some depth within the earth's crust; and to arrange in another series the lavas and tuffs which, thrown out to the surface, bear the closest resemblance to the ejected materials from modern volcanoes. He is thus presented with the records of hypogene igneous action in the one group, and with those of superficial volcanic action in the other. He is furnished with a method of chronologically arranging the volcanic phenomena of past ages, and is thereby enabled to collect materials for a history of volcanic action over the globe.

In adopting this classification for unravelling the geological structure of a region where igneous rocks abound, the student will encounter instances where it may be difficult or impossible to decide in which group a particular mass of rock must be placed. He will bear in mind, however, that after all, such schemes of classification are proposed only for convenience in systematic work, and that there are no corresponding hard and fast lines in nature. He will recognize that all crystalline or glassy igneous rocks must be intrusive at a greater or less depth from the surface, for every contemporaneous sheet has obviously proceeded from some internal pipe or mass, so that though interbedded and contemporaneous with the strata at the top, it is intrusive in relation to the strata below.

The characters by which an eruptive (igneous) rock may be distinguished are partly lithological and partly geotectonic. The lithological characters have already been fully given (Book II. p. 129). Among the more important of them are the predominance of silicates, and notably of felspars, hornblende, mica, augite, olivine, &c.; a prevailing more or less thoroughly cystalline structure; the frequent presence of vitreous matter, either macroscopically or microscopically; and the occurrence of porphyritic, cellular, pumiceous, slaggy, and amygdaloidal structures. These characters are never all united in the same rock. They possess likewise various values as marks of eruptivity, some of them being shared with the crystalline schists which were certainly not eruptive. On the whole, the most trustworthy lithological evidence of the eruptive character of a rock is the presence of glass, or traces of an original glassy base. We do not yet certainly know of any natural vitreous substance except of an eruptive nature. The occurrence or association of certain minerals, or varieties of minerals, in a rock

may also afford presumptive evidence of its igneous origin. Sanidine, leucite, olivine, nepheline, for example, are for the most part characteristic volcanic minerals, and mixtures of finely crystallized triclinic felspars with dark augite, olivine, and magnetic iron, or with hornblende, are specially met with among eruptive rocks.

But it is the geotectonic characters on which the geologist must chiefly rely in establishing the eruptive nature of rocks. These vary according to the conditions under which the rocks have consolidated. We shall consider them as they are displayed by the Plutonic, or deep-seated, and Volcanic, or superficial phase of eruptivity.

Section I. Plutonic, Intrusive or subsequent Phase of Eruptivity.

We have here to consider the structure of those eruptive masses which have been injected or intruded into other rocks, and have consolidated beneath the surface. One series of these masses is crystalline in structure, but with felsitic and vitreous varieties. It includes most of the eruptive rocks, and especially the older forms (granite, syenite, quartz-porphyry, pitchstone, diorite, &c.). The other series is fragmental in character, and includes the agglomerates and tuffs which have filled up volcanic orifices.

After some practice, the field-geologist acquires a faculty of discriminating, even in hand-specimens, crystalline rocks which have consolidated beneath the surface from those which have flowed out as lava-streams. Coarsely crystalline granites and syenites, with no trace of any vitreous ground-mass, are readily distinguishable as plutonic masses; while, on the other hand, cellular or slaggy lavas are easily recognized as superficial outflows, or as closely connected with them. But it will be observed that such differences of texture, though furnishing useful helps, are not to be regarded as always and in all degrees perfectly reliable. We find, for example, that some lavas have appeared at the surface with so coarsely crystalline a structure as to be readily mistaken by a casual observer for granite; while, on the other hand, though an open pumiceous or slaggy structure is certainly indicative of a lava that has consolidated at or near the surface, a finely cellular character is not wholly unknown in intrusive sheets and dykes which have consolidated below ground. Again, masses of fragmentary volcanic material are justly regarded as proofs of the superficial manifestation of volcanism, and in the vast majority of cases they occur in beds which were accumulated on the surface as the result of successive explosions. Yet cases, which will be immediately described, may be found in many old volcanic districts where such fragmentary materials have fallen back into the volcanic funnels, and filling them up have been compacted there into solid rock, or where they may occasionally have been produced by explosions of lava within subterranean caverns.

The general law which has governed the intrusion of igneous

rock within the earth's crust may be thus stated: Every fluid mass impelled upwards by pressure from below, or by the expansion of its own imprisoned vapour, has sought egress along the line of least resistance. That line has depended in each case upon the structure of the terrestrial crust and the energy of eruption. It may have been determined by an already existent dislocation; by planes of stratification, by the surface of junction of two unconformable formations, by irregular contemporaneously formed cracks, or by other more complex lines of weakness. Sometimes the intruded mass has actually fused and obliterated some of the rock which it has invaded, incorporating a portion into its own substance. The shape of the channel of escape has thus determined the external form of the intrusive mass, as the mould regulates the form assumed by cast-iron. This relation offers a very convenient means of classifying the intrusive rocks. According to the shape of the mould in which they have solidified, they may be arranged as—(1) bosses or amorphous masses, (2) sheets, (3) veins and dykes, and (4) necks.

§ 1. Bosses.

Bosses or amorphous masses consist chiefly of crystalline coarse-textured rocks. Granite and syenite are the most conspicuous, but various quartz-porphyries, felsites, diorites, trachytes, dolerites, &c., also occur. Where rocks assume this form as well as that of sheets, dykes, and contemporaneous beds, it is commonly observed that they are more coarsely crystalline when in amorphous masses than in any other form. Doleritic rocks afford many examples of this characteristic. In the basin of the Forth, for instance, while the outflows at the surface have been fine-grained basalts and anamesites, the masses consolidated underneath have generally been coarse dolerites and diabases.[1]

Granite.—It was once a firmly-held tenet that granite is the oldest of rocks, the foundation on which all other rocks have been laid down. This idea no doubt originated in the fact that granite is found rising from beneath gneiss, schist, and other crystalline masses, which in their turn underlie very old stratified formations. The intrusive character of granite, shown by its numerous ramifying veins, proved it to be later than at least those rocks which it had invaded. Nevertheless the composition and structure of gneiss and mica-schist were believed to be best explained by supposing these rocks to have been derived from the waste of granite, and thus, though the existing intrusive granite had to be recognized as posterior in date, it was regarded as only a subsequent protrusion of the vast underlying granitic crust. In this way the idea of the primæval or fundamental nature of granite held its ground. From what is known regarding the fusion and consolidation of rocks (*ante*, p. 292, *seq.*); and from the evidence supplied by the microscopic

[1] *Trans. Roy. Soc. Edin.* xxix. p. 493 (1879).

structure of granite itself, it appears now to be established that granite has always consolidated under great pressure, in presence of superheated water, with or without liquid carbon dioxide, fluorine, &c. (*ante*, pp. 295, 302), conditions which probably never obtained at the earth's immediate surface, unless perhaps in those earliest ages when the atmosphere was densely loaded with vapours and when the atmospheric pressure at the surface must have been enormous (p. 33). But whether the original crust was of a granitic or of a glassy character, no trace of it has ever been or is ever likely to be found.

The presence of granite at the existing surface is, therefore, in all cases due to the removal by denudation of masses of rock under which it originally consolidated. The fact that, wherever extensive denudation of an ancient series of crystalline rocks has taken place, a subjacent granite nucleus is apt to appear, does not prove that rock to be of a primæval origin. It shows, however, that the lower portions of crystalline rocks very generally assume a granitic type, and it suggests that if at any part of the earth we could bore deep enough into the crust we should probably come to a granitic layer. That this layer, even if general round the globe, is not everywhere of the highest geological antiquity, or at least has consolidated at widely different periods, is abundantly clear from the fact that in many cases it can be proved to be of later date than fossiliferous formations the geological position of which is known; that is, the granitic layer has invaded these formations, rising up through them, and probably melting down portions of them in its progress. Granite invades and alters rocks of all ages up to late Mesozoic or Tertiary formations. Hence it does not belong exclusively to the earliest nor to any one geological period, but rather it has been extruded at various epochs, and may even be in course of extravasation now, wherever the conditions required for its production have existed. As a matter of fact granite occurs much more frequently in association with older, and therefore lower, than with newer and higher rocks. But a little reflection shows that this ought to be the case. Granite having a deep-seated origin must rise through the lower and more ancient masses before it can reach the overlying more recent formations. But many protrusions of granite would doubtless never ascend beyond the lower rocks. Subsequent denudation would be needed to reveal these protrusions, and this very process would remove the later formations and at the same time any portions of the granite which might have reached them.

Granite frequently occurs in the central parts of mountain chains; sometimes it forms there a kind of core to the various gneisses, schists, and other crystalline rocks. More frequently it appears in large eruptive bosses, which traverse indifferently the rocks on the line of which they rise, and commonly send out abundant veins into them. Sometimes it even overlies schistose and

other rocks, as in the Piz de Graves in the upper Engadine, where a wall-like mass of granite, with syenite, diorite, and altered rocks, may be seen resting upon schists.[1] In the Alps and other mountain ranges it is found likewise in large bed-like masses which run in the same general direction as the rocks with which they are associated.

Relation of Granite to contiguous Rocks.—From an early period the attention of geologists has been given to the evident mineralogical change which has taken place among stratified rocks as they approach a mass of granite. This change has been specially studied in some European areas, of which those of the Vosges, the Hartz, Devon and Cornwall, Ireland, Scotland and Norway, are well known. The nature of the metamorphism thus superinduced upon rocks is more particularly discussed at p. 578.

The south-east of Ireland supplies an admirable illustration of the relation between granite and its surrounding rocks (Fig. 269). A mass of granite 70 miles in length and from 7 to 17 in width there stretches from north-east to south-west, nearly along the strike of the Lower Silurian rocks. These strata, however, have not been upraised by it in such a way as to expose their lowest beds dipping away from the granite. On the contrary, they seem to have been contorted prior to the appearance of that rock; at least they often dip towards it, or lie horizontally or undulate upon it, apparently without any reference to movements which

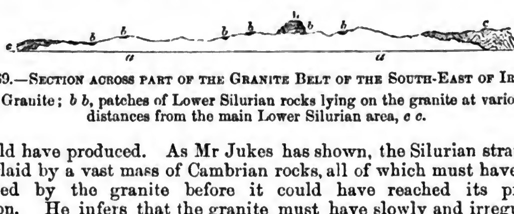


FIG 269.—SECTION ACROSS PART OF THE GRANITE BELT OF THE SOUTH-EAST OF IRELAND.
a, Granite; *b b*, patches of Lower Silurian rocks lying on the granite at various distances from the main Lower Silurian area, *c c*.

it could have produced. As Mr Jukes has shown, the Silurian strata are underlaid by a vast mass of Cambrian rocks, all of which must have been invaded by the granite before it could have reached its present horizon. He infers that the granite must have slowly and irregularly eaten its way upward through the Silurian rocks, absorbing much of them into its own mass as it rose. For a mile or more the stratified beds next the granite have been altered into mica-schist, and are pierced by numerous veins from the invading rock. Within the margin of the granitic mass belts or rounded irregular patches of schist (*b b*) are enclosed; but in the central tracts where the granite is widest, and where therefore we may suppose the deepest parts of the mass have been laid bare, no such included patches of altered rock occur. From the manner in which the schistose belt is disposed round the granite, it is evident that the upper surface of the latter rock where it extends beneath the schists must be very uneven. Doubtless the granite rises in some places much nearer to the present surface of the ground than at others, and sends out veins and strings which do not appear above ground. If, as Mr Jukes supposes, a thousand feet of the schists could be restored at some parts

[1] Studer, "Geologie der Schweitz," i. p. 290.

of the granite belt, no doubt the belt would there be entirely buried; or if, on the other hand, the same thickness of rock could be stripped off some parts of the band of schist, the solid granite underneath would be laid bare. The extent of granite surface exposed must thus be largely determined by the amount of denudation, and by the angle at which the upper surface of the granite is inclined beneath the schists. Where the inclination is high, prolonged denudation will evidently do comparatively little in widening the belt. But where the slope is gentle, and especially where the surface undulates, the removal for some distance of a comparatively slight thickness of rock may uncover a large breadth of underlying granite.[1] Portions of the metamorphosed rocks left by denudation upon the surface of the granite boss, are relics of the deep cover under which the granite no doubt originally lay, and being tougher than the latter rock they have resisted waste so as now to cap hills and protect the granite below, as at Lugnaquilla (L, in Fig. 269).

Recent observations by Professor Hull and Mr. Traill, of the Geological Survey of Ireland, have shown that in the Mourne Mountains a mass of granite has in some parts risen up through highly inclined Silurian rocks, which consequently seem to be standing almost upright upon an underlying boss of granite. The strata are sharply truncated by the crystalline mass, and are indurated but not otherwise altered. The intrusive nature of the granite is well shown by the way in which numerous dykes of dark melaphyre are cut off when they reach that rock.[2] The accompanying diagram (Fig. 270) is taken from

Fig. 270.—Section of Slievenamaddy, Mourne Mountains.

a, a, Lower Silurian strata dipping at high angles; *b, b*, Dykes of basalt (melaphyre), cutting these strata but truncated by the granite *c*, which along the outer margin and in extruded veins passes into a quartz-porphyry, *d, d*.

one of the sections in which this remarkable structure is portrayed by these observers.

In the Lower Silurian tract of the south of Scotland several large intrusive bosses of granite occur (Fig. 271). The strata do not dip away from them on all sides, but with trifling exceptions maintain their normal N.E. and S.W. strike up to the granite on one side, and resume it again on the other. The granite indeed has not merely pushed aside the strata so as to make its way past, but actually occupies the place of so much Silurian greywacke and shale, which have disappeared as if they had been blown out or had been melted up into the granite. There is usually a metamorphosed belt of about a mile in width in which, as they approach the granite, the stratified rocks assume a schistose or gneissoid character. Numerous small, dark, often angular patches or fragments of mica-schist may be observed in the marginal parts of the

[1] See Jukes's *Manual of Geology*, 3rd ed. p. 243.
[2] *Horizontal Section No. 22, Geol. Surv. Ireland.*

granite.[1] Occasionally granite-veins protrude from the main masses, but in the metamorphosed zone which surrounds the Criffel granite area in Kirkcudbright, hundreds of dykes and veins of various felsitic or elvanitic rocks occur.

Similar features are presented by the granite bosses of Devon and Cornwall, which have been risen through Devonian and Carboniferous strata. The Dartmoor mass is specially instructive. As shown by the

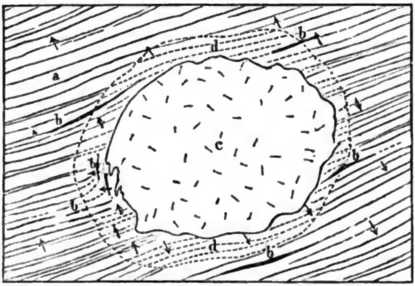


FIG. 271.—PLAN OF GRANITE BOSS, CAIRNSMORE OF FLEET, SCOTLAND.

The granite area (*c*) is from 7 to 10 miles in diameter, rising through highly inclined Lower Silurian strata (*a*), among which are some conspicuous bands of black anthracitic and graptolitic shales (*b*). The arrows show the direction of dip; the parallel lines that of the strike. The ring within the dotted line round the granite defines the belt of metamorphism.

early work of De la Beche, it passes across the boundary between the Devonian and Carboniferous areas, extending chiefly into the latter, so that it cuts across strata of different ages. In doing so it has risen irresistibly through the crust without seriously affecting the general strike of the rocks. It cuts off the ends of old volcanic bands, and of associated grits and shales into which it sends veins.[2]

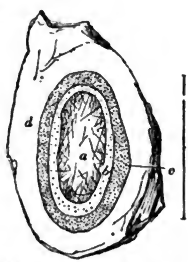


FIG. 272.—CRYSTALLINE GEODE IN GRANITE, DARTMOOR (*B.*).

[1] Round the marginal portions of many granite bosses the rock abounds in such crystalline enclosures (p. 133). The more angular and irregularly shaped of these, evidently portions of the surrounding rocks caught up in the granite, are commonly fragments of mica-schist, gneiss, &c., retaining their foliation, which may have been developed in them after their disruption and enclosure in the granite. Other rounded concretions and cavities lined or filled with crystals are due to irregular segregation in the mass of granite. Examples of this nature occur in the Cornish and Devon granite, as in Fig. 272, which is cited by De la Beche as showing a central cavity (*a*), not quite filled with long crystals of schorl surrounded with an envelope of quartz and schorl (*b*), outside of which lies a second envelope of the same minerals, the schorl predominating, the whole being contained in a light flesh-coloured and markedly felspathic granite. See a paper by J. A. Phillips, *Q. J. Geol. Soc.* xxxvi. p. 1.

[2] De la Beche, "Report, Devon and Cornwall," p. 165.

Connection of Granite with Volcanic Rocks.—The manner in which some bosses of granite penetrate the rocks among which they occur strongly recalls the structure of volcanic necks or pipes. The granite is found as a circular or elliptical mass which seems to descend vertically through the surrounding rocks without seriously altering or disturbing them, as if a tube-shaped opening had been blown out of the crust of the earth up which the granite had risen. Several of the granite masses of the south of Scotland above referred to exhibit this character very strikingly (Fig. 271). That granite and granitoid rocks have probably been associated with volcanic action is indicated by the way in which they occur in connection with the Tertiary volcanic rocks of Skye, Mull, and other islands in the Inner Hebrides. Mr. Jukes suggested many years ago that granite or granitoid masses may lie at the roots of volcanoes and may be the source whence the more silicated lavas proceed.[1]

Metamorphic Origin of some Granite.—The association of volcanic action with metamorphism has been already referred to (p. 308). While the instances are few where any satisfactory connection can actually be traced between granitic masses and true lava-form or volcanic rocks, the close relationship between granite and the crystalline schists has long been recognized. Leaving for the present the problem of the origin of these schists, it must be admitted that in some instances at least gneissoid and schistose rocks are the results of the metamorphism of mechanically formed sedimentary strata. That the granite associated with such rocks is of metamorphic origin, that is to say, has been produced by the gradual softening and recrystallization of other rocks at some depth within the crust of the earth, seems in the highest degree probable. This granite is associated with gneiss in such a way as to suggest that both have had a common origin, and as gradations can be traced from this gneiss through less distinctly crystalline schists into unaltered strata, such granite may be looked upon as the extreme of metamorphism, the various schists and gneisses being less advanced stages of the process (p. 578, *seq.*). Provided the chemical composition of the altered rock be similar to that of granite, it is not necessary that the granite resulting from its alteration should be supposed to differ in any noteworthy particular from eruptive granite. The members of the Geological Survey of Ireland have indeed distinguished two granites in Galway, one of which (characterized by the occurrence of orthoclase and oligoclase) they regard as metamorphic, the other (with orthoclase only) as igneous. More recently in the east of the island they have separated two groups of granites, of which the intrusive masses are composed of dark-coloured quartz, orthoclase, albite, and black mica (Mourne Mountains), while the metamorphic variety is formed of grey felspar, quartz, and black mica.

[1] *Manual of Geology*, 2nd ed. p. 93; Geikie, *Trans. Geol. Soc. Edin.* ii. p. 301; Judd *Quart. Journ. Geol. Soc.* xxx. p. 220; Reyer, "Beitrag zur Physik der Eruptionen."

The mineralogical composition of granite formed by the metamorphism of other and specially sedimentary rocks must necessarily vary with that of the masses out of which it has arisen. In some cases there is a regular gradation from true granite outward into the schistose and gneissose masses, of which instructive examples occur in the Scottish Highlands (Part VIII.), and in northern New York and New England.[1] But such a transition need not always occur, for if the granite was subject to unequal pressure (which it assuredly would in most cases be), it would in its soft, pasty condition undoubtedly be squeezed into any rents made in the surrounding rocks, and would thus imitate a truly eruptive mass, which in actual fact it would then be. When granite rises through unaltered or only locally altered strata, it may fairly be termed igneous and intrusive. When, on the other hand, it is intimately associated with extensive masses of schist and gneiss, many of which can only be distinguished from it by their foliated structure, its metamorphic origin may at least be strongly suspected. Fundamentally, indeed, eruptive and metamorphic granite seem to be due only to different modifications of the same subterranean processes. A mass of originally sedimentary rocks may be depressed to a depth of several thousand feet within the earth's crust, where, subjected to vast pressure and considerable heat in presence of interstitial water or steam, it may be metamorphosed into crystalline schist. A portion of this mass, undergoing extreme alteration, may so completely lose all trace of its original fissile structure as to become amorphous crystalline granite, some of which may even be thrust as veins into the less highly changed parts above and around. One stage further would bring before us a connection opened between the earth's surface and such a deep-seated granitic mass, and the consequent ascent and outburst of acid lavas and their fragmental accompaniments (p. 544).[2]

Diorite, &c.—On a smaller scale usually than granite, other crystalline rocks assume the condition of amorphous bosses. Diorite, syenite, quartz-porphyry, and members of the basalt family have often been erupted in irregular masses, partly along fissures, partly along the bedding, but often involving and apparently melting up portions of the rocks through which they have made their way. Such bosses have frequently tortuous boundary-lines, since they send out veins into or cut capriciously across the surrounding rocks. In Wales, as shown by the maps and sections of the Geological Survey, the Lower Silurian formations are pierced by huge bosses of different crystalline rocks, mostly included under the old term "greenstone," which, after running for some way with the strike of the strata, turn round and break across it, or branch and traverse a considerable thickness of stratified rock. In central Scotland numerous masses of dolerite and quartziferous diabase have been intruded among the Lower Carboniferous formations. One horizon on which they are particularly

[1] Dana, *Amer. Jour. Sci.* xx. (1880), p. 194.

[2] See Dana, *op. cit.*

abundant lies about the base of the Carboniferous Limestone series. Along that horizon they rise to the surface for many miles, sometimes ascending or descending in geological position, and breaking here and there abruptly across the strata.[1] There can be little doubt that they have actually melted down some parts of the stratified rocks, particularly the limestone. Considerable petrographical differences occur among them, which may perhaps be in some measure due to the incorporation of such extraneous material into their mass. Gaps occur where these intrusive rocks do not rise to the surface, but as they resume their position again not far off, it may be presumed that they are really connected under these blank intervals.

Mr. G. K. Gilbert has described, under the name of "laccolite," a structure in the Henry Mountains in Southern Utah, which is probably not uncommon in denuded volcanic districts. Large bosses of trachytic lava have risen from beneath, but instead of finding their way to the surface, have spread out laterally and pushed up the overlying strata into a dome-shaped elevation. Here and there smaller

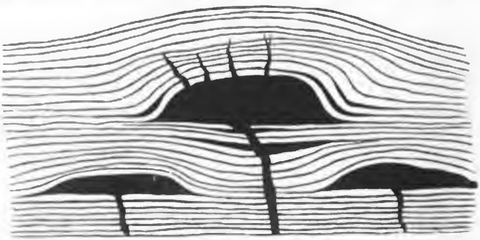


Fig. 273.—Ideal Section of three "Laccolites," after Gilbert.

sheets proceeding from the main masses have been forced between the beds, or veins have been injected into fissures, and the overlying and contiguous strata have been considerably metamorphosed.[2]

Effects on Contiguous Rocks.—Many intrusive bosses have greatly affected the texture, and even the mineralogical composition of the rocks through which they have been erupted. The amount and nature of the change produced vary with the character and bulk of the eruptive mass as well as with the susceptibility of the surrounding materials to alteration. Diorite, diabase, melaphyre, basalt, felsite, and other eruptive rocks are not infrequently accompanied by very considerable metamorphism of the adjacent strata. These phenomena are manifested also by intrusive sheets, dykes, veins, and necks. They belong to the series of changes embraced under the head of contact metamorphism, and are grouped together for description in the next Part (p. 572).

[1] *Trans. Roy. Soc. Edin.* xxix. p. 476.

[2] *Geology of the Henry Mountains*, U.S. Geog. and Geol. Survey, Washington, 1877. The same structure was figured and described upwards of forty years ago by C. Maclaren, "Geol. of Fife and Lothian," 1839, pp. 100, 101.

Connection with Volcanic Action.—There can be little doubt that in regard to eruptive masses, particularly of the dioritic, diabasic, and doleritic or basaltic series, though the portions now visible consolidated under a greater or less depth of overlying material, they must in many cases have been directly connected with superficial volcanic action. Some of them may have been underground ramifications of the ascending molten rock which poured forth at the surface in streams of lava, though these superficial portions have been removed by denudation. Others may mark the position of intruded masses which were arrested in the unsuccessful attempt to open a new volcanic vent.

§ 2. Sheets.

Eruptive masses have been intruded between other rocks, and now appear as more or less regularly defined beds. In almost all cases it will be found that these intrusions have taken place between the planes of stratification. The ascending molten matter, after breaking across the rocks, or rather after ascending through fissures either previously formed or opened at the time of the outburst, has at last found its path of least resistance to lie along the bedding planes of the strata. Accordingly it has thrust itself between the beds, raising up the overlying mass and solidifying as a nearly or exactly parallel cake or sheet.

It is evident that one of these intercalated sheets must present such points of resemblance to a stream of lava that flowed above ground as to make it occasionally a somewhat difficult matter to determine its true character, more especially when, owing to extensive denudation, or other cause, only a small portion of the rock can now be seen. The following characters mark intrusive sheets, though they must not be supposed to be all present in every case. (1.) They do not rigidly conform to the bedding of the rocks among which they are intercalated, but sometimes break across it and run along on another platform. (2.) They catch up and involve portions of the surrounding strata. (3.) They sometimes send veins into the rocks above and below them. (4.) They are connected with dykes or pipes which, descending through the rocks underneath, have been the channels by which the intrusive sheets were supplied. (5.) They are commonly most close-grained at their upper and under surfaces, and most coarsely crystalline in the central portions. (6.) They are rarely cellular or amygdaloidal. (7.) The rocks both above and below them are usually hardened and otherwise more or less altered.

As a well-known and (from its association with the Huttonian and Wernerian disputes) classical example of this structure, the mural escarpment called Salisbury Crags at Edinburgh may be described. This is a sheet of crystalline dolerite which can be traced for a distance of 1500 yards, lying among the red and grey sandstones, shales, and impure limestones, which form the base of the Carboniferous

system of central Scotland. As the general dip of the rocks is north-easterly, it forms a lofty cliff facing west and south, from the base of which a long grassy slope of débris stretches down to the valley in front; the thickness of the sheet at the highest part of the bed is about 80 feet, but at a distance of 650 yards to the north this thickness diminishes to less than a half. At first the dolerite might be taken for a conformable sheet, regularly interposed between the sedimentary strata. But an examination of the beds on which it rests shows that it transgressively passes over a succession of platforms, and eventually comes to rest at the east end on strata somewhat lower in geological position than those at the north end. Moreover, another parallel intrusive

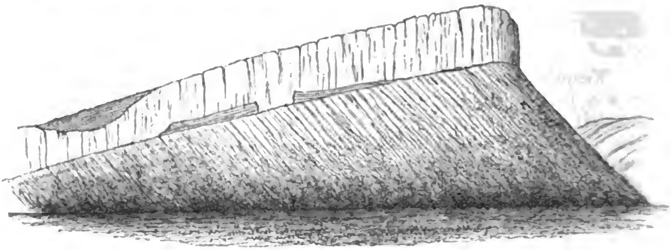


Fig. 274.—Diagrammatic View of Salisbury Crags, Edinburgh.

sheet intercalated in a lower portion of the sandstone series gradually approaches the rock of Salisbury Crags. They are both transgressive across the strata, and they appear to unite in a large mass called Samson's Ribs.

On the west front a large dyke-like mass of the eruptive rock descends vertically through the sandstones, and has been regarded as not improbably a pipe or feeder, from which the molten rock originally rose (Fig. 274). Along the southern face of the escarpment several instructive exposures show the behaviour of the dolerite to the strata through which it has made its way. Fig. 275, for example, represents a portion

Fig. 275.—Section at base of South Front of Salisbury Crags.
Showing portion of strata cut out by intrusive Dolerite. a, sandstones, shales, &c.; b, dolerite. Length of section 22 feet.

of the underlying strata carried away, the dolerite having been wedged in below one of the remaining broken ends. Again, veins and threads of the eruptive rock have been injected into fragments of the strata, caught up in its mass (Fig. 276). The strata in contact with the

dolerite have been much hardened, the shales being converted into a kind of porcellanite, and the sandstones into quartzite.[1] The dolerite in the centre of the bed is a coarse-grained rock, in which the component minerals can readily be detected with a lens, or even with the unassisted eye. But as it approaches the sedimentary beds, above and below, it becomes finely crystalline. I have had sections cut for the microscope, showing the actual junction of the two rocks. (See Fig. 25, p. 148.) In these it is interesting to observe that the dolerite, for about the eighth of an inch inwards from its edge, consists mainly of an altered glass in which lie well-formed crystals of triclinic felspar and numerous opaque tufted microliths, which may be of augite. An inch back from the edge the glass and the microliths have alike disappeared, and the rock is merely a crystalline dolerite, though finer in grain than in the central portions of the bed. Numerous steam or gas vesicles occur in the vitreous part, some of them empty, but mostly filled with calcite or a

FIG. 276.—MASS OF SANDSTONE AND SHALE (*a*) IMBEDDED IN THE DOLERITE (*b*) OF SALISBURY CRAGS, AND INJECTED WITH VEINS AND THREADS OF IT.

brown ferruginous earth. There can be little doubt that the vitreous structure of this marginal film was originally that of the whole rock. The thinness of the glassy crust is in harmony with all that is known as to the feeble thermal conductivity of lava. When the dolerite was intruded it was no doubt a molten glass containing much absorbed vapour, the escape of which at its high temperature was probably the main agent in indurating the adjacent strata. In a number of slices cut from different parts of the central portion of the dolerite, I have failed to detect any of the steam-holes so marked in the outer vitreous edge. The retention of this absorbed vapour in the general mass of the molten rock doubtless facilitated the process of crystallization from the original glassy condition.

This greater closeness of texture at the surfaces of contact forms one of the distinguishing marks of an intrusive as contrasted with a contemporaneous sheet (p. 563). Microscopic examination of these

[1] Mr. Sorby has observed in specimens from this locality sliced by him for microscopic examination that the fluid cavities in the quartz grains have been emptied.—"Address," *Q. J. Geol. Soc.* xxx.

marginal parts from many of the intrusive sheets in central Scotland, shows that even where no distinct glass remains the rock is crowded with black opaque microliths arranged in a delicate geometric network. Back from the surface of contact these microliths disappear, and the magnetite or titaniferous iron assumes its ordinary crystalline and often indeterminate or imperfect contours. Whether these bodies were developed only along the marginal portions of the intrusive mass and belong to conditions of rapid cooling and escape of vapour, or were originally present as incipient forms of crystallization throughout the entire rock, but have been lost in the subsequent growth of the crystalline forms, is not quite clear, though the former supposition seems most probable.

Another lithological characterstic of the intrusive as compared with the interbedded sheets is the considerable variety of composition and structure which may be detected in different portions of the same mass. A rock which at one place gives under the microscope a crystalline-granular texture, with the mineral elements of dolerite, will at a short distance show a coarsely crystalline texture with abundant orthoclase and free quartz—minerals which do not belong to normal dolerite. These differences, like those above referred to as noticeable among amorphous bosses, seem too local and sporadic to be satisfactorily referred to original differences in the composition of various parts of the molten magma, or to segregation by gravitation or otherwise. They suggest rather that great intrusive sheets have here and there involved and melted down portions of rocks, and have thus acquired locally an abnormal composition.[1]

Effects on Contiguous Rocks.—Admirable examples of the alteration produced by eruptive masses are not uncommonly presented at the contact of intrusive sheets with the surrounding rocks. Induration, decoloration, fusion, the production of a prismatic structure, conversion of coal into anthracite, of limestone into marble, and other alterations, may be observed. The nature of these changes is described at p. 572.

Connection with Volcanic Action.—Many volcanic rocks occur in the form of intrusive sheets, as felsite, quartz-porphyry, diorite, melaphyre, diabase, dolerite, basalt, trachyte, and others. The remarks above made regarding the connection of intrusive bosses with volcanic action may be repeated with even greater definiteness here. Intrusive sheets abound in old volcanic districts intimately associated with dykes and surface outflows, and thus bringing before our eyes traces of the underground mechanism of volcanoes. Interesting examples of this connection occur among the Carboniferous volcanic rocks of the basin of the Forth.[2] Many of the "necks" or former volcanic vents are associated with intrusive sheets, which probably mark some of the subterranean protrusions of molten rock

[1] *Trans. Roy. Soc. Edin.* xxix. p. 492. Clough, *Geol. Mag.* 1880, p. 433.
[2] See *Trans. Roy. Soc. Edin.* xxix. p. 474.

during the earlier stages of volcanic action before communication had been established with the surface, or towards the close when, the vents having been choked up with erupted material, escape to the surface became difficult.

§ 3. Veins and Dykes.

The term "vein" is rather vaguely employed by geologists. It is used as the designation of any mass of mineral matter which has solidified between the separated walls of a fissure. When this mineral matter has been deposited from aqueous solution or from sublimation, it forms what is known as a *mineral vein* (p. 589). When it has been injected in a molten or pasty state, it forms an *eruptive vein;* or, if it forms a vertical wall-like mass, a *dyke.* When it has crystallized or segregated out of the component materials of some still unconsolidated, colloid, or pasty rock, it is called a *segregation vein.*

Eruptive or Intrusive Veins and Dykes are portions of once-melted or at least pasty matter which have been injected into

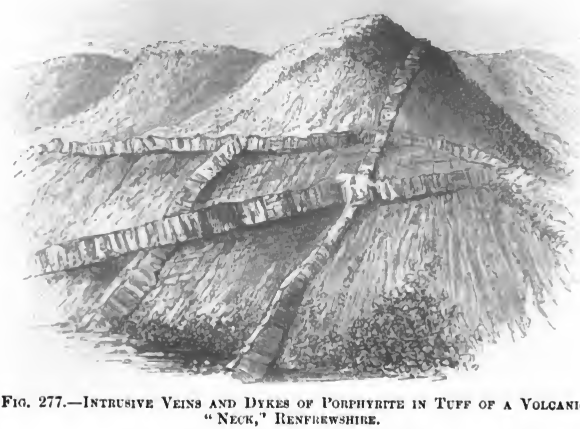


FIG. 277.—INTRUSIVE VEINS AND DYKES OF PORPHYRITE IN TUFF OF A VOLCANIC "NECK," RENFREWSHIRE.

rents of previously solidified rocks. When traceable sufficiently far, they may be seen to swell out and merge into their parent mass, while in the opposite direction they may become attenuated into mere threads. Sometimes they run for many yards in tolerably straight lines, and when this takes place along the stratification

they look like beds. At these parts, they are of course really intrusive sheets. But they may frequently be found to start suddenly upward or downward, and to break across the bedding in a very irregular manner.

No rock exhibits more instructively than granite the numerous varieties of form assumed by veins. One large class of granite veins is probably referable to segregation-veins—indeed in the case of those associated with granitoid gneiss, it seems impossible to draw any line between segregation and eruption. Where veins proceeding from a granite mass traverse disrupted strata of schist or gneiss, they may be intrusive, though this by no means always follows; for in the archæan gneiss of Sutherland the abundant pegmatite veins, even when cutting across disrupted bands of gneiss, pass into others that are interbedded with and graduate insensibly into the gneiss, so that the whole mass, veins and folia alike, must be regarded as due to the same great complex process—that which produced the ancient crystalline schists. Most large masses of granite send veins into the surrounding rocks, and often in such abundance as to form a complicated network (Figs. 278, 279).

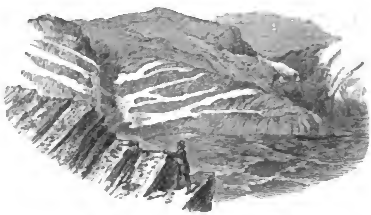


Fig. 278.—Granite Veins.

They vary in breadth from several feet or even yards down to fine filaments at the ends of the smaller branches. They frequently cross each other, not only outside of the granite mass, but even within it. They vary much in texture and in composition. Sometimes they are coarsely crystalline pegmatite, but most of the veins of this kind are doubtless due rather to segregation than intrusion. Large bosses of granite are often traversed by conspicuous veins of pegmatite (Fig. 284), but the veins due most probably to actual intrusion of material, are commonly finer-grained than the main mass. Besides this greater closeness of texture, these intrusive veins sometimes present considerable differences in mineralogical composition. The mica, for example, may be reduced to exceedingly minute and not very abundant flakes, and may almost disappear. The quartz also occasionally assumes a subordinate place, and the rock of the veins passes into eurite, elvanite, or one of the varieties of felsite or quartz-porphyry.[1]

Where granite appears among crystalline schists, the distinctive characters of its intrusive veins are apt to be lost among the abundant

[1] See a reference to the Bodegang, *ante*, p. 134. Mr. Hawes has recently described a similar example from New Hampshire. *Amer. Journ. Sci*, xxi. (1881), p. 244.

proofs of segregation. But where a large boss rises in a region of ordinary sedimentary rocks, these characters are strongly defined. It is in the metamorphosed belt, already (p. 542) described as encircling an intrusive boss of granite, that eruptive veins are typically developed and most readily studied. In Cornwall, for example, the granite and surrounding slates are abundantly traversed by veins or dykes of granite and of quartz-porphyry (*elvans*), which are most numerous near the granite. They vary in width from a few inches or feet to 50 fathoms, their central portions being commonly more crystalline than the sides. They frequently enclose angular fragments of slate (p. 543, *note*). In the great granite region of Leinster Mr. Jukes traced some of the elvans for several miles running in parallel bands, each only a few feet thick, with intervals of 200 or 300 yards between them. Around some of the granite bosses of the south of Scotland similar veins of felsite and

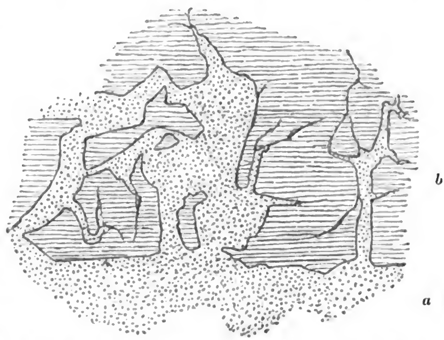


FIG. 279.—SECTION OF GRANITE (*a*), SENDING A NETWORK OF VEINS INTO SLATE (*b*), CORNWALL (*B.*).

porphyry abound. The granite of the Wahsatch Mountains in Utah, which rises through the Upper Carboniferous limestones, converting them into white marble, sends out veins of granite-porphyry and other crystalline compounds. In short, all over the world it is common for eruptive bosses of this rock to have a fringe of intrusive veins (Fig. 280).

Many other eruptive rocks (diorite, diabase, melaphyre, basalt, &c.) present admirable examples of intrusive veins. These are distinguished from those of granite by the much less metamorphism with which they are attended.

Dykes are veins of eruptive rock, filling vertical or highly-inclined fissures, and are so named on account of their resemblance to walls (*Scotice*, dykes). Their sides are often as parallel and perpendicular as those of built walls, the resemblance to human workmanship being heightened by the numerous joints which, intersecting each other along the face of a dyke, remind us of well-fitted masonry. Where the surrounding rock has decayed, the dykes

may be seen projecting above ground exactly like walls (Fig. 281); indeed in many parts of the west of Scotland they are made use of for enclosures. The material of the dykes has in other cases decayed, and deep ditch-like hollows are left to mark their sites. The coast-

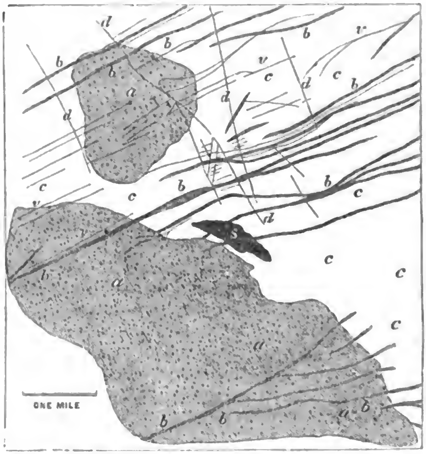


Fig. 280.—Map of part of the Mining District of Gwennap, Cornwall (*B.*).
a a, Granite; *c c*, Schistose rocks; *b b*, Elvan dykes; *s*, "Greenstone," *v v*, *d d*, two intersecting series of mineral veins.

lines of many of the Inner Hebrides and of the Clyde Islands furnish numerous admirable examples of both kinds of scenery.

The term dyke might be applied to some of the wall-like intrusions of quartz-porphyry, elvanite, and even of granite, but it is more typically illustrated among the augitic igneous rocks, such as basalt, diabase, &c., though also among diorites, porphyries, pitchstones, &c., while occasionally dykes may be observed even of tuff and volcanic agglomerate. While veins have been injected into irregular branching cracks, dykes have been formed by the welling upwards of liquid or plastic rock in vertical or steeply inclined fissures, though obviously there is no essential difference between the two forms of structure. Sometimes the line of escape has been along a fault. In Scotland, however, which may be regarded as a typical region for this kind of geological structure, the vast majority of dykes rise along fissures which have no throw, and are therefore not faults. On the contrary, the dykes may be traced undeflected across some of the largest faults in the midland counties.

Dykes differ from veins in the greater parallelism of their sides, their verticality, and their greater regularity of breadth and persistence of direction. They sometimes occur as mere plates of rock not more than an inch or two in thickness, at other times they attain a breadth of twelve fathoms or more. The smaller or thinner dykes can seldom be traced more than a few yards; but the larger examples may be followed sometimes for miles. Thus in the south and west of Scotland a remarkable series of basalt-dykes can be traced across all the geological formations of that region, including

FIG. 281.—DYKES IN VOLCANIC TUFF OF A "NECK," SHORE, ELIE, FIFE.

the older Tertiary basalt. They run parallel to each other in a general north-west and south-east direction for distances of 20 and 30 miles, and have been assigned to the great volcanic activity of the Miocene period. A remarkable dyke of the same series crosses the north of England from near the coast of Yorkshire for fully 60 miles inland.

Though the wall-like form is predominant among dykes, it may readily pass into vein-like ramifications and into intrusive sheets (Fig. 277). The molten material took the channels that happened to be most available. If the fissure bent off at an angle from its previous course, or if another adjacent fissure happened to be more convenient, the eruptive rock might change its course. Again, while the chief mass of ascending lava rose in one main fissure, portions of it might find their way into neighbouring parallel rents, and enclose wall-like portions of rock within the dyke, as in Fig. 282, where the total breadth of the main dyke, including the sandstone between the two arms, is about 30 feet, the sandstone being gently inclined, and the portion enclosed within the corner of the dyke having been greatly indurated.

In internal structure considerable differences may be detected among dykes. The rock may appear (*a*) with no definite structure of any kind beyond irregular jointing; (*b*) columnar, the prisms striking off at right angles from the walls, and either going completely across from side to side or leaving a central non-columnar part in which they branch and lose themselves: when the side of a dyke having this structure is laid bare, it presents a network of polygonal joints formed by the ends of the prisms which, when the dyke is vertical, lie of course in a horizontal position, whence they depart in proportion as the dyke is inclined: occasionally the prisms are as well-formed as in any columnar bed of basalt; (*c*) jointed parallel with the walls, the joints being sometimes so close as to cause the rock to appear as if it consisted of a series of vertical plates or strata: this platy character when it occurs in basalt dykes is best developed along the walls; (*d*) vesicular or amygdaloidal, lines of minute vesicles having been formed parallel with the walls, and attaining their greatest number and size along the centre of the dyke.

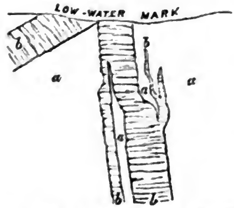


Fig. 282.—Plan of Dyke cutting Sandstones, Shore, Gourock, Renfrewshire.

As a rule, the outer parts of a dyke of crystalline rock are finer-grained than the centre. Occasionally the external surface has a vitreous structure precisely analogous to that already described in the case of intrusive sheets (p. 549). Basalt veins, for example, have not infrequently an external coating or varnish (tachylite, hyalomelan, &c.). It occasionally happens also that the central portions of a dolerite dyke are glassy, of which structure several cases have been observed in Scotland; perhaps in these instances the dyke has opened along its centre and a fresh uprise of more glassy basalt has risen in the fissure.[1]

Effects on Contiguous Rocks.—These are similar to the changes produced by intrusive sheets and other eruptive masses. Induration is the most frequent kind of alteration. Remarkable examples have been observed where, in limestones in contact with dykes, a saccharoid crystallization of the calcite has been superinduced, and where even new crystalline silicates have been developed (p. 572).

Segregation Veins.—These include most of what were formerly and not very happily termed "contemporaneous veins," and are peculiar to crystalline rocks, abounding in many granites, likewise in some gneisses and schists, and not infrequently to be observed in sheets of diorite, dolerite, and diabase. They run as straight, curved, or branching ribands, seldom exceeding a foot in thickness. Sometimes they are finer in texture than the rock which

[1] See *Proc. Roy. Phys. Soc. Edin.* vol. v. 1880, p. 241.

they traverse, though the reverse is frequently the case, more especially in granite. Close examination of them shows that instead of being sharply defined by a definite junction line with the enclosing rock, they are welded into that rock in such a way that they

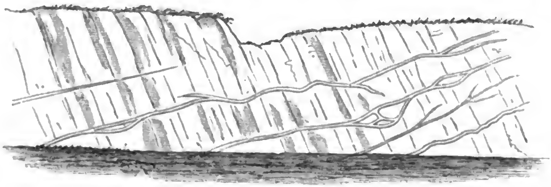


FIG. 283.—SEGREGATION VEINS IN DIABASE.

cannot easily be broken along the plane of union. This welding is found to be due to the mutual protrusion of the component crystals of the vein and of the surrounding rock—a structure sometimes admirably revealed under the microscope. Veins of this kind evidently point to some process, still unexplained, whereby into rents

FIG. 284.—PEGMATITE VEIN ASSOCIATED WITH FOLIATED GRANITE. RUBISLAW QUARRY, ABERDEEN.

g g, Ordinary granite of the mass; *p p*, coarse pegmatite veins; *s s*, foliated granite passing insensibly into *g*; *q*, mass of quartz. The black patches in *p* and *q* are nests of schorl.

formed in the deeply buried, and at least partially consolidated or possibly colloid mass, there was a transfusion or exosmosis of some of the crystallizing minerals. Along the margin of segregation veins in granite a foliated structure of the rock may be occasionally observed, as in some of the large granite quarries near Aberdeen (Fig. 284).

Coarse pegmatite veins abounding in large plates of muscovite, black tourmaline, and quartz, with occasional crystals of beryl and other minerals, merge into the surrounding granite, which for a few inches along the contact has a foliated structure precisely resembling that of a fine gneiss. Possibly this foliation may indicate motion of the granite mass along the line of fissure, while the rock itself or the materials of the fissure were still capable of molecular rearrangement.[1]

§ 4. Necks.

Under this term are included the filled-up pipes or funnels of former volcanic vents. Every series of volcanic sheets poured out at the surface must have been connected either with fissures or with orifices probably opened in lines of fissure. On the cessation of the eruptions, the orifices have remained filled with lava or with fragmentary matter. But unless subsequent denudation has removed the overlying cone, a vent lies buried under the materials which came out of it. So extensive, however, has been the waste of the surface in many old volcanic regions that the vents have been laid

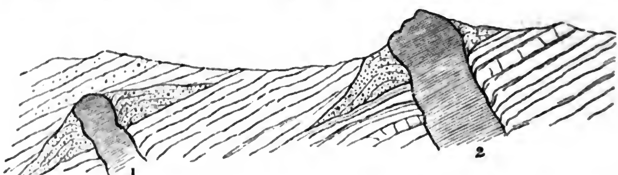


Fig. 285.—Diagram-section to show the Structure of Old Volcanic Vents, and how they may be concealed and exposed.

1. Tuff cone with basalt plug still buried under sedimentary accumulations; 2. Tuff cone and basalt plug partially exposed by denudation.

bare. In Fig. 285, two volcanic funnels are represented, one of them still buried under overlying formations, the other partially exposed by denudation. Such accumulations of volcanic material in and around the pipes of eruption are known as **Necks**. The study of them brings before us some of the more deep-seated phenomena of volcanic action that cannot usually be seen at a modern volcano.

A neck is circular or elliptical in ground-plan, but occasionally more irregular and branching, and may vary in diameter from a few yards up to a mile, or even more (Fig. 286). It descends into the earth perpendicularly to the stratification of the formation to which it belongs. Should rocks originally horizontal be subsequently tilted, a neck associated with them would of course be thrown out of the vertical (Fig. 285). As a rule, however, the vertical descent of the necks into the earth's crust has been comparatively little interfered with. In external form necks commonly rise as cones or dome-

[1] See pp. 307, 313.

shaped hills (Fig. 287). This contour, however, is not that of the original volcanoes, but is due to denudation. Occasionally the rocks of a neck have been so worn away that a great hollow, suggestive of the original crater, occupies their site. (Fintry Hills, Stirlingshire.)

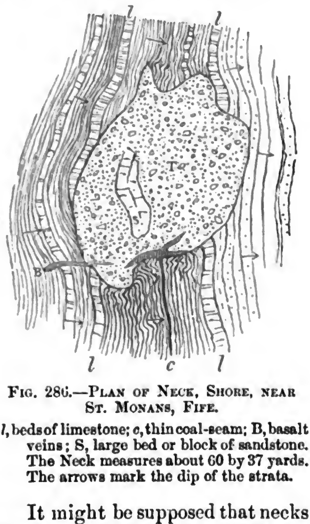


FIG. 286.—PLAN OF NECK, SHORE, NEAR ST. MONANS, FIFE.

l l, beds of limestone; *c*, thin coal-seam; B, basalt veins; S, large bed or block of sandstone. The Neck measures about 60 by 37 yards. The arrows mark the dip of the strata.

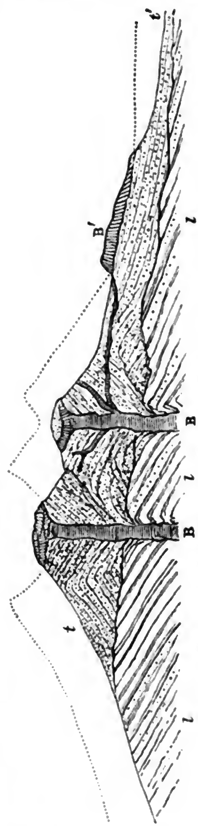


FIG. 287.—SECTION OF THE VOLCANIC NECK OF LARGO LAW, FIFE.

l l, Lower Carboniferous strata; *t*, tuff of cones; *t'*, tuff of area around the cones; B B, basalt filling central pipes of the vents and lateral veins; B' basalt, which may have flowed out at the surface. The dotted lines are suggestive of the original outline of the hill.

It might be supposed that necks should always rise on lines of fissure. But in central Scotland, where they abound in rocks of Carboniferous age, it is quite exceptional to find one placed on a fault. As a rule, they seem to be independent of the structure of the crust through which they rise.

The materials filling up ancient volcanic orifices may be (*a*) some form of lava, as felstone, quartz-porphyry, diabase, porphyrite, basalt; or (*b*) the fragmentary materials which fell back into the throat of the volcano and finally solidified there. In many instances both kinds of rock occur in the same neck, the main mass consisting of agglomerate or tuff with a central pipe or numerous veins of lava. Among the Palæozoic

volcanic districts of Britain necks not infrequently are filled with some siliceous crystalline rock, such as a quartz-porphyry or felsite, even where the surrounding lavas are basic. The great vent of the Braid Hills near Edinburgh, belonging to the time of the Lower Old Red Sandstone, is filled with felsite tuff containing 70 per cent. of silica, where the lavas which flowed from it are basic porphyrites with not more than 50 per cent. of this acid. Again, at Largo in Fife, strings of quartz-felsite occur in one of the necks, though all the surrounding lavas are basalts. Necks of agglomerate and fine tuff abound among the Carboniferous and Permian volcanic regions of Scotland, and are laid bare in so many admirable sections, that these regions may be regarded as typical for this kind of geological structure.

The fragmentary materials in necks consist mainly of different lava-form rocks imbedded in a gravelly *peperino*-like matrix of more finely comminuted débris of the same rocks; but they also contain, sometimes in abundance, fragments of the strata through which the necks have been drilled. Occasionally, as in some of the Maare of the Eifel, these non-volcanic fragments constitute most of the débris (p. 243). When this is the case we may infer that after the first gaseous explosions, the activity of the vent ceased, without the rise of the lava column or its ejection in dust and fragments to the surface. So unchanged are many of the pieces of sandstone, shale, limestone, or other stratified rock in the necks, that they have evidently never been exposed to any high temperature. In some cases, however, considerable alteration is displayed. Dr. Heddle, from observations in Fife, concluded that the altered blocks in the tuff there must have been exposed to a temperature of between 660° and 900° Fahr.[1]

Among the numerous vents of central Scotland pieces of fine stratified tuff not infrequently appear in the agglomerates. This fact, coupled with the not uncommon occurrence of a tumultuous, fractured, and highly-inclined bedding of the tuff with a dip towards the centre of the neck (Figs. 287, 288), appears to show that the pipes were partly filled up by the subsidence of the tuff consolidated in beds within the crater and at the upper part of the funnel. Further indication of the probable subaerial character of the tuff is furnished by abundant pieces of enclosed coniferous wood, which may have belonged to trees or brushwood that grew upon the dry slopes of the cones; for these fragments are seldom to be seen in the estuarine and marine strata, out of which the cones rose.

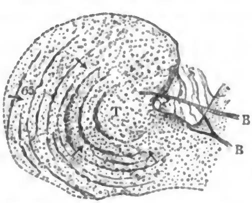


Fig. 288.—Plan of Neck, on Shore, at Elie, Fife.

T, tuff; the arrows marking the inward Dip; S, sandstones through which the Neck has been blown open; B B, basalt dykes.

[1] *Trans. Roy. Soc. Edin.* xxviii. p. 487.

It is common to find among necks of tuff, numerous dykes and veins of lava which, ascending through the tuff, are usually confined to it, though occasionally they penetrate the surrounding strata. They are often beautifully columnar, the columns diverging from the sides of the dykes and being frequently curved.

Proofs of subsidence round the sides of vents may often be observed. Stratified rocks through which a volcanic funnel has been opened commonly dip into it all round, and may even be seen on edge, as if they had been dragged down by the subsidence of the materials in the vent. Beautiful examples occur along the shores of the Firth of the Forth.[1] The fact of subsidence beneath modern volcanic cones has been already referred to (pp. 232, 243).

Effects on Contiguous Rocks.—The strata round a neck are usually somewhat hardened. Sandstones have acquired sometimes a vitreous lustre; argillaceous beds have been indurated into porcellanite; coal-seams have been burnt and rendered unworkable. The coal-workings in Fife and Ayrshire have revealed many interesting examples of these changes, which may be partly due to the heat of the ascending column of molten rock or ejected fragments, partly to the rise of heated vapours, even for a long time subsequently to the volcanic explosions. Proofs of a metamorphism probably due to the latter cause may sometimes be seen within the area of a neck. Where the altered materials are of a fragmentary character, the nature and amount of this change can be best estimated. What was originally a general matrix of volcanic dust has been converted into a crystalline and even porphyritic mass, through which the dispersed blocks of the agglomerate, though likewise intensely altered, are still recognizable. Such blocks as, from the nature of their substance, must have offered most resistance to change,—pieces of sandstone or quartz, for example,—stand out prominently in the altered mass,

FIG. 289.—SECTION ACROSS THE BINN OF BURNTISLAND, FIFE.
1, Sandstones; 2, Limestone; 3, Shales, &c.; *b b*, Interstratified basalts; *t t*, Bedded tuffs, &c.; T, Tuff of the great neck of the Binn; B, Basalt veins.

[1] *Trans. Roy. Soc. Edin.* xxix. p. 469. For an excellent example from New Zealand see *Q. J. Geol. Soc.* 1860, p. 245.

though even they have undergone more or less modification, the sandstone being converted into vitreous quartz-rock.[1]

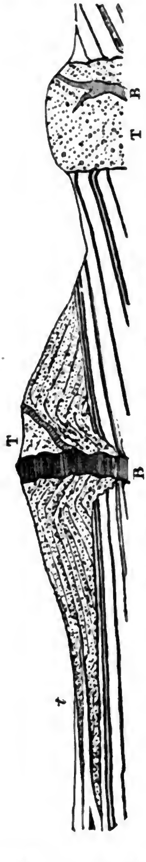


Fig. 290.—Section across the Saline Hills, Fife.
T, Tuff of necks; *t*, Continuation of tuff of cone intercalated with the contemporaneously formed sedimentary strata; B, Basalt. The thick parallel lines are coal-seams which are burnt round the smaller eminence, or Knock Hill, while they can be worked for some way under the larger, or Saline Hill.

Section II. Interbedded Volcanic or Contemporaneous Phase of Eruptivity.

Masses of igneous materials, ejected to the surface in some of the forms now visible in modern volcanoes, possess great value as fixing the geological epoch of volcanic eruptions. It is evident that on the whole such superficial masses must agree in lithological characters with rocks already described, which have been extravasated by volcanic efforts without quite reaching the surface. Yet they have some well-marked general characters, of which the most important may be thus stated. (1.) They occur as beds or sheets, sometimes of lava-form, sometimes of fragmental materials, which conform to the bedding of the strata among which they are intercalated. (2.) They do not break into or alter overlying strata. (3.) The upper and under surfaces of the lava-beds present commonly a scoriaceous or vesicular character, which may even be found extending throughout the whole of a sheet. (4.) Fragments of these upper surfaces not unusually occur in the immediately overlying strata. (5.) Beds of tuff are frequently interstratified with sheets of lava.

§ 1. Crystalline, or Lavas.

While the underground course of a protruded mass of molten igneous rock has widely varied according to the shape of the channel through which it proceeded and in which, as in a mould, it solidified, the behaviour of the rock, once poured out at the surface, has been much more uniform. As in modern lava, the erupted mass has rolled along, varying in thickness and other minor

[1] For a detailed account of the structure of some volcanic necks the student may consult a monograph by the author on the Carboniferous volcanic rocks of the Basin of the Forth. *Trans. Roy. Soc. Edin.* xxix. p. 437.

characters, but retaining the broad general aspect of a lenticular bed or sheet. A comparison of such a bed with one of the intrusive sheets already described shows that in several important lithological characters they differ from each other. An intrusive sheet is closest in grain near its upper and under surfaces. A contemporaneous bed or true lava-flow, on the contrary, is there usually most open and scoriaceous. In the one case we rarely see vesicles or amygdules, in the other they often abound. However rough the upper surface of an interbedded sheet may be, it never sends out veins into nor encloses portions of the superincumbent rocks, which, however, sometimes contain portions of it, and wrap round its hummocky irregularities. Occasionally it may be observed to be full of rents which have been filled up with sandstone or other sedimentary material. These rents were formed while the lava was cooling, and sand was subsequently

FIG. 291.—SANDSTONE (*s*) FILLING RENTS IN THE SURFACE OF AN INTERBEDDED SHEET OR FLOW OF PORPHYRITE (*p*). COAST OF KINCARDINESHIRE.

The rents have been filled in with sand before the eruption of the next flow.

washed into them. Examples of this structure abound among the porphyrites of the volcanic tracts of the Scottish Lower Old Red Sandstone. The amygdaloidal cavities throughout an interbedded sheet, but more especially at the top, may often be noticed with an elongated form, and even pulled out into tube-like hollows in one general direction, which was obviously the line of movement of the yet viscous mass (pp. 89, 477). Some kinds of rock when occurring in interbedded sheets are apt to assume a system of columnar jointing. Basalt in particular is distinguished by the frequency and perfection of its columns. The Giant's Causeway and the cliffs of Staffa, of Ardtun in Mull, of Loch Staffin in Skye, the Orgues d'Expailly in Auvergne, and the Kirschberg of Fulda are well-known examples (*ante*, p. 506).

Interbedded lavas of former geological periods, like those of

recent date (*ante*, p. 239), occur under the two tolerably well-defined conditions of crater and fissure-eruptions.

1. Single lenticular sheets or groups of sheets, usually of limited extent and with associated bands of tuff, form the more frequent type among Palæozoic and Secondary formations. A single interbedded sheet may occasionally be found intercalated between ordinary sedimentary strata without any other volcanic accompaniment. But this is unusual. In the great majority of cases several sheets will be found together, with accompanying bands of contemporaneous tuff.

In such abundantly volcanic districts as central Scotland, the necks or vents of eruption (p. 558) may frequently be detected around the lavas which proceeded from them. The thickness of an interbedded sheet varies for different kinds of lava. As a rule, the more acid rocks are in thicker beds than the more basic. Some of the thinnest and most persistent sheets may be observed among the basalts, where a thickness of not more than 12 or 15 feet for each sheet is not uncommon. Both individual sheets and groups of sheets possess a markedly lenticular character. They may be seen to

Fig. 292.—Four successive Flows of Porphyrite, Lower Carboniferous, East Linton.

thicken in a particular direction, probably that from which they flowed. Thus in Linlithgowshire a mass of lavas and tuffs, reaching a collective thickness of probably 2000 feet in the Carboniferous Limestone series, rapidly dies out, until within a distance of only ten miles it dwindles down to a single band less than fifty feet thick. On the other hand, beds of tolerably uniform thickness and flatness of surface may be found; among the basalts, more particularly, the same sheet may be traceable for miles, with remarkable regularity of thickness and parallelism between its upper and under surfaces (p. 565). The porphyrites and trachytic and felsitic lavas are more irregular in thickness and form of surface (Fig. 292).

Interbedded (and also intrusive) sheets have shared in all the subsequent curvatures and faultings of the formations among which they lie. This relation is well seen in the "toadstones" or diabase beds associated with the Carboniferous Limestone of Derbyshire (Fig. 293).[1]

2. The second type is displayed in widespread plateaux composed of many successive sheets, frequently with little or no intercalation of tuff. It occurs even among Palæozoic formations, but

[1] See Section 18, "Hor. Sect. Geol. Surv. Great Britain."

attains its greatest development among the volcanic eruptions of Tertiary time. Instead of mere local lenticular patches, these sheets lie piled over each other sometimes to a depth of several thousand feet, and frequently cover areas of many thousand square miles. Among the Palæozoic rocks of Scotland remnants of such ancient volcanic plateaux occur in the Old Red Sandstone (hills of Lorne) and Carboniferous systems (Campsie Fells and hills above Largs), where they consist chiefly of consecutive sheets of different porphyrites rising into long terraced tablelands. The regularity of thickness and parallelism of these sheets form conspicuous features in the scenery of the districts in which they occur.

It is chiefly basaltic rocks, however, that in all parts of the world have escaped in fissure eruptions and now build up vast volcanic plateaux. The fragmentary Miocene plateaux of the British Islands, the Faroe Islands, and Iceland; those of the Indian Deccan and of Abyssinia, and the more recent basalt floods which have closed the eventful history of volcanic action in North America, are notable illustrations of this type of structure. Beds of tuff, conglomerate, gravel, clay, shale, or other stratified intercalations

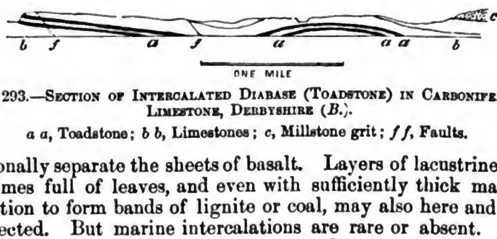


FIG. 293.—SECTION OF INTERCALATED DIABASE (TOADSTONE) IN CARBONIFEROUS LIMESTONE, DERBYSHIRE (*B.*).

a a, Toadstone; *b b*, Limestones; *c*, Millstone grit; *f f*, Faults.

occasionally separate the sheets of basalt. Layers of lacustrine clays, sometimes full of leaves, and even with sufficiently thick masses of vegetation to form bands of lignite or coal, may also here and there be detected. But marine intercalations are rare or absent. There can be no doubt that these widely extended sheets of basalt were in the main subaërial outpourings, and that in the hollows of their hardened surfaces lay lakes and smaller pools of water in which the interstratified sedimentary materials were laid down. The singular persistence of the basalt-beds has often been noticed. The same sheet may be followed for several miles along the magnificent cliffs of Skye and Mull. Mr. Clarence King believes that single sheets of basalt in the Snake River lava-field of Idaho may have flowed for 50 or 60 miles.[1] The basalts, however, so exactly resemble each other that the eye may be deceived unless it can follow a band without any interruption of continuity.

§ 2. Fragmental, or Tuffs.

While the observer may be in doubt whether a particular bed of lava has been poured out at the surface as a true flow or has con-

[1] "Geological Exploration of 40th Parallel," i. p. 593.

solidated at some depth, and therefore whether or not it is to be regarded as evidence of an actual volcanic outbreak at the locality, he is not liable to the same uncertainty among the fragmental eruptive rocks. Putting aside the occasional brecciated structure seen along the edges of plutonic intrusive masses, he may regard all the truly fragmental igneous rocks as proofs of volcanic action having been manifested at the surface. The agglomerate found in a volcanic neck could not have been formed unless the vapours in the vent had been able to find their way to the surface, and in so doing to blow into fragments the rocks on the site of the vent as well as the upper part of the ascending lava-column.[1] Wherever therefore a bed or a series of beds of tuff occurs interstratified in a geological formation it points to contemporaneous volcanic eruptions. Hence the value of these rocks in interpreting the volcanic annals of a region.

The fragmentary ejections from a volcano or a cooling lava-stream vary from the coarsest agglomerate to the finest tuff, the coarser materials being commonly found nearest to the source of

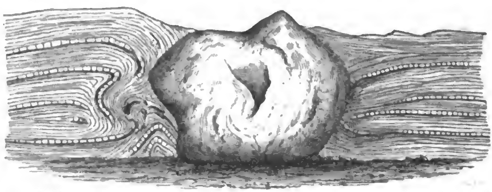


Fig. 294.—Ejected Volcanic Block (12 × 15 × 17 inches) in Lower Carboniferous Shales, Pettycur, Fife.

discharge. They differ in composition, according to the nature of the lavas with which they are associated and from which they have been derived. Thus a region of trachyte-lavas, supplies trachyte-tuffs and trachyte-breccias; one of basalts gives basalt-breccias, basalt-agglomerates, basalt-tuffs; one of obsidians yields pumiceous tuffs and breccias. The fragmentary matter ejected from volcanic vents, has fallen partly back into the funnels of discharge, partly over the surrounding area. It is therefore apt to be more or less mingled with ordinary sedimentary detritus. We find it indeed passing insensibly into sandstone, shale, limestone, and other strata. Alternations of gravelly *peperino*-like tuff with a very fine-grained "ash" may frequently be observed. Large blocks of lava-form rock, as well as of the strata through which the volcanic explosions have taken place, occur in the tuffs of most old volcanic districts. Occasionally such ejected blocks or bombs are found among fine shales

[1] It is conceivable that where a mass of lava was injected into a subterranean cavern fragmentary discharges might take place and partly fill that cavity; but such exceptional cases are probably rare.

and other strata, the lamination of which is bent down round them in such a way as to show that the stones fell with considerable force into the still soft and yielding silt or clay (Fig. 294).[1]

Fragmentary materials frequently occur in interstratified beds without any accompanying lava; this takes place much more commonly than do interstratified sheets of lava without beds of tuff, just as in recent volcanic districts it is more usual to find cones of ashes or cinders without lava than lava sheets without an accompaniment of ashes. Masses of fine or gravelly tuff several hundreds of feet in thickness, without the intervention of any lava-bed, may be observed in the volcanic districts of the Old Red Sandstone and Carboniferous systems in Scotland, evidence of long-continued volcanic action, during which fragmentary materials were showered out and spread over the water-basins mingled with little or no ordinary sediment. On the other hand, in these same areas thin seams of tuff interlaminated with sandstone, shale, or limestone, afford indications of feeble intermittent volcanic explosions, whereby light showers of dust were discharged, which settled down quietly amidst the sand, mud, or limestone accumulating around at the time. Under these latter circumstances tuffs often become fossiliferous; they enclose the remains of such plants and animals as might be lying on the lake-bottom or sea-floor over which the showers of volcanic dust fell, and thus they form a connecting link between aqueous and igneous rocks.

As illustrations of the nature of the stratigraphical evidence for former conditions of volcanic activity, two sections from Linlithgowshire may here be given. In the first of these (Fig. 295), a black shale (1) of

FIG. 295.—SECTION OF INTERSTRATIFICATIONS OF TUFF AND SHALE, OLD QUARRY, WESTER OCHILTREE, LINLITHGOWSHIRE (LOWER CARBONIFEROUS).

the usual carbonaceous type, with remains of terrestrial plants, lies at the bottom. It is covered by a bed of nodular bluish-grey tuff (2) containing black shale fragments, whence we may infer that the underlying or some similar shale was blown out from the site of the vent that furnished this dust and gravel. A second black shale (3) is succeeded by a second thin band of fine pale yellowish tuff. Black shale (5) again

[1] See *Geol. Mag. I.* (1864), p. 22.

supervenes, containing rounded fragments of tuff, perhaps lapilli intermittently ejected from the neighbouring vent, and passing up into a layer of tuff (6), which marks how the volcanic activity gradually increased again. It is evident that, but for the proximity of an active volcanic vent, there would have been a continuous deposit of black shale, the conditions of sedimentation having remained unchanged. In the next stratum of shale (7), thin seams and nodules of clay-ironstone accumulated round decomposing organic remains on the muddy bottom. A brief volcanic explosion is marked by the thin tuff-bed (8), after which the old conditions of deposit continued, the bottom of the water (as the shale (9) shows) being crowded with ostracod crustaceans, while fishes, whose coprolites have been left in the mud, haunted the locality. At last, however, a much more powerful and prolonged volcanic explosion took place. A coarse agglomeratic tuff (10), with blocks sometimes nearly a foot in diameter, was then thrown out and overspread the lagoon.

Fig. 296.—Section in Wardlaw Quarry, Linlithgowshire.

The second example (Fig. 296) brings before the mind a volcanic episode of another kind, in the history of the same region. At the bottom of the section a pale amygdaloidal, somewhat altered basalt-rock (A) marks the upper surface of one of the submarine lavas of the Carboniferous Limestone period. Directly over it comes a bed of limestone (B) 15 feet thick, the lower layers of which are made up of a dense growth of the thin-stemmed coral, *Lithostrotion irregulare*, which overspread the hardened lava. The next stratum is a band of dark shale (C), about 2 feet thick, followed by about the same thickness of an impure limestone with shale seams. The conditions for coral growth were evidently not favourable; for the deposit of this argillaceous limestone was arrested by the precipitation of a dark mud, now to be seen in the form of 3 or 4 inches of a black pyritous shale (E), and next by the inroad of a large quantity of a dark sandy mud, and drift vegetation,

which has been preserved as a sandy shale (F), containing *Calamites*, *Producti*, ganoid scales, and other traces of the terrestrial and marine life of the time. Finally a sheet of lava, represented by the uppermost amygdaloid (C), overspread the area, and sealed up these records of Palæozoic history.[1]

PART VIII.—THE CRYSTALLINE SCHISTS AS PART OF THE ARCHITECTURE OF THE EARTH'S CRUST.—METAMORPHISM, LOCAL AND REGIONAL.

§ I. General Characters.

Possessing characters which on the one hand link them with stratified, on the other with eruptive rocks, the crystalline schists present a peculiar type of structure with which are connected some of the most perplexing problems of geology. These rocks cover extensive areas of the surface of the continents, occurring usually wherever the oldest formations have been brought to the light. But they everywhere pass under younger formations, so that their visible superficies is probably but a very small part of their total extent. In the northern regions of Europe and of North America they spread over thousands of square miles, forming the tableland of Scandinavia, the Highlands of Scotland, and a great part of Eastern Canada and Labrador. They likewise commonly rise to the surface along the axes of great mountain chains in all quarters of the globe. So persistent are they that the belief has arisen that they everywhere underlie the stratified formations as a general foundation or platform. Some details of their structure will be given in the description of Archæan rocks in Book VI.

The most distinctive character of the schists is undoubtedly their foliation (p. 118). They have usually a more or less conspicuous crystalline structure, though occasionally this is associated with traces and even very prominent manifestations of clastic ingredients (pp. 123, 125). Their foliated or schistose structure varies from the massive type of the coarsest gneiss down to the extremely delicate arrangement of the finest talcose or micaceous schist. They occur sometimes in monotonous uniformity; one rock, such as gneiss or mica-schist, covering vast areas. In other places they consist of rapid alternations of various foliated masses—gneiss, mica-schist, clay-slate, actinolite-schist, and many other species and varieties. Lenticular seams of crystalline limestone or marble, usually with some of the minerals mentioned on p. 114, sometimes strongly graphitic, not unfrequently occur among them, especially where they contain bands of serpentine or other magnesian silicates. Thick irregular zones of magnetite, hæmatite, and aggregates of hornblendic, pyroxenic, or chrysolitic minerals likewise make their appearance.

[1] See "Memoirs of Geol. Survey, Geology of Edinburgh," pp. 45, 58. *Trans. Roy. Soc. Edin.* xxix. p. 483.

Another characteristic of the schists is their usual intense crumpling and plication. The thin folia of their different component minerals are intricately and minutely puckered (Fig. 19). Thicker bands may be traced in violent plication along the face of exposed crags. So intense indeed have been the internal movements of these masses that the geologist experiences great and often insurmountable difficulties in trying to make out their order of succession and their thickness. Such evidence of disturbance, though usually strongly marked, is not everywhere equally so. Some areas have been more intensely crumpled and plicated, and where this is the case the rocks usually present their most conspicuously crystalline structure.

A further eminently characteristic feature of the schists is their common association with bosses and veins or bed-like sheets of granite, syenite, quartz-porphyry, or other massive rocks. In some regions indeed so abundant are the granitic masses and so coarsely crystalline or granitoid the schists, that it becomes hardly possible to draw satisfactory boundary lines between the two kinds of rock.

Apart from disputed theories as to the mode in which the crystalline schists were formed, there seems no good reason to doubt that originally these rocks were laid down in sheets or beds, and that their present puckered and plicated condition has been the result of terrestrial movements similar to those by which the crumpling and plication of ordinary sedimentary rocks in mountain regions have been produced. The alternations of different bands of quartzose, aluminous, or magnesian composition, with the occasional intercalation of lenticular zones of white marble, at once recall the manner in which deposits of sandstone and shale, associated with each other in the older geological formations, are here and there interrupted by courses of limestone. This first postulate, therefore, is generally granted, that the crystalline schists were deposited on the sea-floor.

But the next step in the induction has given rise to great differences of opinion. Some geologists maintain that the crystalline schists are original chemical deposits of the primeval ocean. Others insist that these rocks were at first mere mechanical, possibly to some extent chemical, sediments, and that their present crystalline and foliated characters have been superinduced upon them ; in other words that they are metamorphic rocks. One of the chief causes of the difficulty of the problem lies in the fact that the crystalline schists are in the majority of cases separated from all other geological formations by an abrupt hiatus. Instead of passing into these formations they are commonly covered unconformably by them, and have usually been enormously denuded before the deposition of the oldest overlying rocks. Hence, not only is there a want of continuity between the schists and younger formations, but the contrast between them in regard to lithological characters and geotectonic structure is so exceedingly striking as naturally to suggest the idea that the schists must belong to a period long anterior to that of the earliest sedimentary formations of the ordinary

type and to a totally different order of physical conditions. Natural, however, as this conclusion may be, those who adopt it probably seldom realise to what an extent it rests upon mere assumption. Starting with the supposition that the crystalline schists are the result of geological operations that preceded the times when ordinary sedimentation began, it assumes that they belong to one great early geological period. Yet all that can logically be asserted as to the age of these rocks is that they must be older than the oldest formations which overlie them. If in one region of the globe they appear from under Cretaceous, in another below Carboniferous, in a third below Silurian strata, their chronology is not more accurately definable from this relation than by saying they are respectively pre-Cretaceous, pre-Carboniferous, and pre-Silurian. They may all of course belong to the same period; but where they occur in detached and distant areas their synchronism cannot be proved. To assert it is an assumption which, though in many cases irresistible, ought not to be received with the confidence of an established truth in geology.

In the investigation of the problem of the crystalline schists much assistance may be derived from a study of the localities where a crystalline and foliated structure has been superinduced upon ordinary sedimentary rocks—where, in fact these rocks have actually been changed into schists, and where the gradation between their unaltered and their altered condition can be clearly traced. Accordingly the following pages of this Part will be devoted to an examination of the salient features of metamorphism and metamorphic rocks.

At the outset some caution must be employed as to the use of the terms "metamorphism" and "metamorphic." It is obvious that we have no right to call a rock metamorphic unless we can distinctly trace it into an unaltered condition, or can show from its internal composition and structure that it has undergone a definite change, or can prove its identity with some other rock whose metamorphic character has been satisfactorily established. Further, it must be remembered that in a certain sense, all or nearly all rocks may be said to have been metamorphosed, since it is exceptional to find any, not of very modern date, which do not show, when closely examined, proofs of having been hardened by the pressure of superincumbent rock and altered by the action of percolating water or other daily acting metamorphic agent. Even a solid crystalline mass which, when viewed on a fresh fracture with a good lens, seems to consist of unchanged crystalline particles, will usually betray under the microscope unmistakable evidence of alteration. And this alteration may go on until the whole internal organization of the rock, so far at least as we can penetrate into it, has been readjusted, though the external form may still remain such as hardly to indicate the change, or to suggest that any new name should be given to the recomposed rock. Among many igneous rocks, particularly the

more basic kinds, as basalts, diorites, olivine rocks, &c., alteration of this nature may be studied in all its stages. (See pp. 107, 331.)

But mere alteration by decay is not what geologists denote by metamorphism. The term has been, indeed, much too loosely employed; but it is now generally used to express a change in the mineralogical or chemical composition and internal structure of rocks, produced at some depth from the surface through the operation of heat, and heated water or vapour. A metamorphic rock may be as compact and crystalline as the parent mass from which it has been altered, like which, also, when exposed at the surface, it again undergoes alteration by weathering.

Metamorphism may be effected: 1st. By the action of heated water carrying carbonic acid and mineral solutions produced by carbonic or other acid (p. 300); 2nd. By the action of hot vapours and gases (pp. 235, 297); 3rd. By the heat generated in the crushing of rock-masses during contraction of the terrestrial crust (p. 290); 4th. By the intrusion of heated eruptive rocks, sometimes containing a large proportion of absorbed water, vapours, or gases (p. 541 *seq.*); 5th. Occasionally and very locally by the combustion of beds of coal.

Metamorphism is manifested in two distinct phases. 1st. Local (the metamorphism of contact or of juxtaposition), where the change has been effected only within a limited area beyond which the ordinary condition of the altered rocks can be seen. 2nd. Regional (normal), where the change has taken place over a large tract, the original characters of the altered rocks being more or less completely effaced.

§ II. **Local Metamorphism** (metamorphism of contact or juxtaposition).

The influence of thermal waters in effecting mineralogical changes within rocks has been already described, and some illustrative examples have been given (pp. 299, 309). Such changes may take place along the sides of the channels in which the heated water makes its way to the surface, and as far into the rock around as the water may be able to penetrate. Eruptive rocks, also, when intruded among limestones, sandstones, shales, and other sedimentary formations, produce in them various kinds and degrees of alteration.

Bleaching is well seen at the surface, where heated volcanic vapours rise through tuffs or lavas and convert them into white clays (p. 235). Decoloration, however, has proceeded also underneath, along the sides of dykes (p. 553). Thus in Arran a zone of decoloration ranging from 5 or 6 to 25 or 30 feet in width, runs in the red sandstone along each side of many of the abundant basalt dykes. This removal of the colouring peroxide may have been effected by the prolonged escape of hot vapours from the cooling lava of the dykes. Had it been due merely to the reducing effect of organic matter in the meteoric water filtering down each side of the

dyke, it ought to occur as frequently along joints in which there has been no ascent of igneous matter.

Colouration.—Rocks, particularly shale and sandstone, in contact with intrusive sheets, are sometimes so reddened as to resemble the burnt shale from an ironwork. Every case of reddening along a line of junction between an eruptive and non-eruptive rock, must not, however, be set down without examination as an effect of the mere heat of the injected mass, for sometimes the colouring may be due to subsequent oxidation of iron in one or both of the rocks by water percolating along the lines of contact.

Induration.—One of the most common changes superinduced upon sedimentary rocks along their contact with intrusive masses is a hardening of their substance. Sandstone, for example, is converted into a compact substance which breaks with the lustrous fracture of quartzite. Argillaceous strata are altered into flinty slate, Lydian stone, jasper, or porcellanite. This change may sometimes be produced by mere dry heat, as when clay is baked. But probably in the majority of cases, induration of subterranean rocks results from the action of heated water. The most obvious examples of this action are those wherein the percentage of silica has been increased by the deposit of a siliceous cement in the interstices of the stone, or by the replacement of some of the mineral substances by silica. This is specially observable round eruptive masses of granite and some diabases.[1]

Expulsion of water.—One effect of the intrusion of molten matter among the ordinary cool rocks of the earth's crust has doubtless often been temporarily to expel their interstitial water. The heat may even have been occasionally sufficient to drive off water of crystallization or of chemical combination. Mr. Sorby mentions that it has been able to dispel the water present in the minute fluid cavities of quartz in a sandstone invaded by dolerite.[2]

Prismatic structure.—Contact with eruptive rocks has frequently produced a prismatic structure in the contiguous masses. Conspicuous illustrations of this change are displayed in sandstones through which dykes have risen (Fig. 297). Independently of the lines of stratification polygonal prisms, six inches or more in diameter, and several feet in length, starting from the face of the dyke, have been developed in the sandstone.[3]

Some of the most perfect examples of superinduced prisms may occasionally be noticed in seams of coal which have been invaded by

[1] Kayser, on contact metamorphism amid the diabase of the Harz, *Z. Deutsch. Geol. Ges.* xxii. 103, where analyses showing the high percentage of silica are given. Hawes, *Amer. Journ. Sci.* January 1881. The phenomena of metamorphism round granite are further described below p. 578 *seq.*

[2] *Q. J. Geol. Soc.* 1880.

[3] Sandstone altered by basalt, melaphyre, or allied rock, Wildenstein, near Büdingen, Upper Hesse; Schöberle, near Kriebitz, Bohemia; Johnsdorf, near Zittau, Saxony; Bishopbriggs, near Glasgow.

intrusive igneous material. In the Scottish coal-fields sheets of basalt have been forced along the surfaces of coal-seams, and even along their centre so as to form a bed or sheet in the middle of the coal. The coal in these cases is sometimes beautifully columnar, its slender hexagonal and pentagonal prisms, like rows of stout pencils, diverging from the surface of the intrusive sheet.[1]

Other examples of the production of this structure have been described in dolomite altered by quartz-porphyry (Campiglia, Tuscany); fresh-water limestone altered by basalt (Gergovia, Auvergne); basalt-tuff and granite altered by basalt[2] (Mt. Saint-Michel, Le Puy).

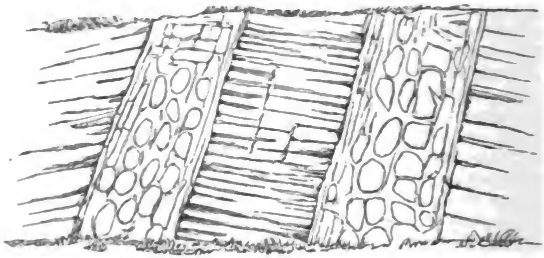


Fig. 297.—Sandstone (*a*, *a*) rendered Prismatic by Dolerite (*b*, *b*), Bishopbriggs, Glasgow.

Calcination, Melting, Coking.[3]—By the great heat of erupted masses, more especially of basalt and its allies, some rocks have undergone partial fusion, their matrix or some of their component minerals having been melted, while others have been entirely fused. Among granite fragments ejected with the slags of old volcanic vents in Auvergne, some present no trace of alteration, others are burnt as if they had been in a furnace, or are partially melted so as to look like slags, each of their component minerals, however, remaining distinct. In the Eifel volcanic region, the fragments of mica-schist and gneiss ejected with the volcanic detritus have sometimes a crust or glaze of glass. Sandstones, though most frequently baked into a compact quartzite, are sometimes changed into an enamel-like mass in which,

[1] Coal and lignite, with their accompanying clays, altered by basalt, diabase, melaphyre, &c., Ayrshire, Scotland; St. Saturnin, Auvergne; Meissner, Hesse Cassel; Ettingshausen, Vogelsgebirge; Sulzbach, Upper Palatinate of Bavaria: Fünfkirchen, Hungary: by trachyte, Commentry, Central France; by phonolite, Northern Bavaria.

[2] Naumann, "Geognosie," i. p. 737.

[3] It is worthy of observation that changes of the kind here referred to occur most commonly with basalt-rocks, melaphyres, and diabases. Trachyte has been a less frequent agent of alteration, though some remarkable examples of its influence have been noted. Poulett Scrope (*Geol. Trans.* 2nd Ser. II.) describes the alteration of a trachyte conglomerate by trachyte into a vitreous mass. Quartz-porphyry and diorite occasionally present examples of calcination, or more or less complete fusion. But with the granitic and syenitic rocks changes of this kind have never been observed. Naumann, "Geognosie," i. p. 744.

when the rock consists of an argillaceous or calcareous matrix with dispersed quartz-grains, the infusible quartz may be recognized (Oberellenbach, Lower Hesse). According to Bunsen's observations, volcanic tuff and phonolite have sometimes been melted for several feet on the sides of the dolerite dykes which traverse them, so as to present the aspect of pitchstone or obsidian.[1] Besides complete fusion and fluxion structure there has sometimes been also a production of microscopic crystallites in the fused portions resembling those of eruptive rocks.

The effects of eruptive rocks upon carbonaceous beds and particularly upon coal-seams are among the most conspicuous examples of this kind of alteration. They vary considerably, according to the bulk and nature of the eruptive sheet, the thickness, composition, and structure of the coal-seam, and probably other causes. In some cases the coal has been fused and has acquired a blistered or vesicular texture, the gas cavities being either empty or filled with some infiltrated mineral, especially calcite (east of Fife). In other examples the coal has become a hard and brittle kind of anthracite or "blind coal," owing to the loss of its more volatile portions (west of Fife). This change may be observed in a coal-seam six or eight feet thick, even at a distance of 50 yards from a large dyke. Traced nearer to the eruptive mass the coal passes into a kind of pyritous cinder scarcely half the original thickness of the seam. At the actual contact with the dyke it becomes by degrees a kind of caked soot, not more perhaps than a few inches thick (South Staffordshire, Ayrshire). Coal altered into a prismatic substance has been above (p. 573) referred to; it has even been observed changed into graphite (New Cumnock, Ayrshire).

The basalt of Meissner (Lower Hesse) overlies a thick stratum of brown coal which shows an interesting series of alterations. Immediately under the igneous rock a thin seam of impure earthy coal ("letten") appears as if completely burnt. The next underlying stratum has been altered into metallic-lustred anthracite, passing downwards into various black glossy coals beneath which the brown coal is worthless. The depth to which the alteration extends is 5·3 metres.[2] Another example of alteration has recently been described by G. vom Rath from Fünfkirchen in Hungary.[3] A coal-seam has there been invaded by a basic igneous rock (perhaps diabase) now so decomposed that its true lithological character cannot be satisfactorily determined. Here and there the intrusive rock lies concordantly with the stratification of the coal, in other places it sends out fingers, ramifies, abruptly ends off, or occurs in detached nodular fragments in the coal. The latter in contact with the intrusive naterial is converted into prismatic coke. The analysis of three specimens of the coal throws light on the nature of the change.

[1] Usually the vitreous band at the margin of a dyke of basalt or dolerite is tachylitic, belonging to the intruded rock and not to that through which it has risen.

[2] Moesta, "Geologische Schilderung, Meissner und Hirschberge," Marburg, 1867.

[3] G. vom Rath, *N. Jahrb.* 1880, p. 276. In the above analysis the bitumen includes all volatile constituents driven off by heat, hence coke and bitumen = 100.

One of these (A) shows the ordinary composition of the coal at a distance from the influence of the intrusive rock, the second (B) taken from a distance of about 0·3 metres (nearly 1 foot) exhibits a partial conversion into coke, while in the third (C), taken from immediate contact with the eruptive mass, nearly all the volatile hydrocarbons have been expelled.

	Ash.	Sulphur.	Coke.	Bitumen.
A.	8·29 per cent.	2·074	79·7	20·3
B.	9·73 "	1·112	87·8	12·2
C.	45·96 "	0·151	95·3	4·7

In a coal-field much invaded by igneous rocks the seams of coal are usually found to have suffered more than the other strata, not merely because they are specially liable to alteration from the proximity of heated surfaces, but because they have presented lines of more easy escape for the igneous matter pressed from below. The molten rock has very generally been injected along the coal-seams; sometimes taking the lower, sometimes the upper surface, or even, as already stated, forcing its way along the centre.

During the subterranean distillation arising from the destruction or alteration of coal and bituminous shales, while the gases evolved find their way to the surface, the liquid products, on the other hand, are apt to collect in fissures and cavities. In central Scotland, where the coal-fields have been so abundantly pierced by igneous masses, petroleum and asphaltum are of frequent occurrence, sometimes in chinks and veins of sandstones and other sedimentary strata, sometimes in the cavities of the igneous rocks themselves. In West Lothian intrusive sheets, traversing a group of strata containing seams of coal and oil-shale, have a distinctly bituminous odour when freshly broken, and little globules of petroleum may be detected in their cavities. In the same district the joints and fissures of a massive sandstone are filled with solid brown asphalt which the quarrymen manufacture into candles.

Striking as is the change produced by the intrusion of basalt into coals and bituminous shales, it is hardly more conspicuous than the alteration effected on the invading rock. A compact crystalline black heavy basalt or dolerite, when it sends sheets and veins into a coal or highly carbonaceous shale, becomes yellow or white, earthy, and friable, loses weight, ceases to have any apparent crystalline texture, and, in short, passes into what would at first unhesitatingly be pronounced to be mere clay. It is only when the distinctly intrusive character of this substance is recognized in the veins and fingers which it sends out, and in its own irregular course in the altered coal, that its true nature is made evident. Microscopical examination shows that this "white-rock" or "white-trap" is merely an altered form of some diabasic or basaltic rock, wherein the felspar crystals, though much decayed, can yet be traced, the augite, olivine, and magnetite being more or less completely changed into a mere pulverulent earthy substance. A specimen of this altered rock analysed by Henry gave :—Alumina, 13·250; Silica, 38·830; Lime, 3·925; Magnesia, 4·180; Soda, 0·971; Potash, 0·422; Protoxide of iron, 13·830; Peroxide of iron, 4·335; Carbonic acid, 9·320; Water, 11·010 = 100·073. It is evident that part of the lime, magnesia, and alkalies, and some of the silica, have here been removed, and that most of the iron exists as ferrous carbonate.

Marmarosis.[1]—The conversion of ordinary dull granular limestone into crystalline or saccaroid marble may not infrequently be observed on a small scale where an intrusive sheet or dyke has invaded the rock. One of the earliest described examples of this change is that at Rathlin Island off the north coast of Ireland (Fig. 298). Two basalt dykes (20 and 35 feet thick respectively)

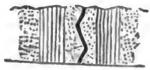


FIG. 298.—DYKES OF BASALT (*a a a*) TRAVERSING CHALK (*b*), WHICH NEAR THE DYKES IS CONVERTED INTO MARBLE (*c*), RATHLIN ISLAND, ANTRIM.

ascend there through chalk, of which a band twenty feet thick separates them. Down the middle of this central chalk band runs a tortuous dyke one foot thick. The chalk between the dykes and for some distance on either side has been altered into a finely granular marble.[2] Another smaller but interesting illustration of the same change occurs at Camps Quarry near Edinburgh. The dull grey Burdie House limestone (Lower Carboniferous), full of valves of *Leperditia* and plants, has there been invaded by a basaltic dyke, which, sending slender veins into the limestone, has enclosed portions of it. The limestone is found to have acquired the granular crystalline character of marble, each little granule of calcite having its own orientation of cleavage planes (Fig. 299).

Production of new minerals.—One of the results of the intrusion of eruptive rock has been the development of crystalline minerals in ordinary sedimentary strata near the line of contact. The new minerals have usually an obvious affinity in composition with the original rock. But undoubtedly silica has often been introduced as part of the alteration, either free or as silicates.

FIG. 299.—SECTION OF LIMESTONE (*a*) (BURDIE HOUSE) CONVERTED INTO GRANULAR MARBLE BY BASALT (*b*). MAGNIFIED 20 DIAMETERS.

An interesting instance of the change was described many years ago by Henslow, near Plas Newydd, Anglesea. A basalt dyke 154 feet in breadth there traverses strata of shale and argillaceous limestone, which are altered to a distance of 35 feet from the intrusive rocks, the limestone becoming granular and crystalline, and the shale being hardened, here

[1] The coining of a new word to express a change for which there is as yet no short term may perhaps be pardoned.

[2] Conybeare, *Trans. Geol. Soc.* iii. p. 210 & Plate x.

and there porcelainized, while its shells (*producti*, &c.), though nearly obliterated, are still traceable by their impressions. In the altered fossiliferous shale numerous crystals of analcime and garnet have been developed, the latter yielding as much as 20 per cent. of lime.[1] Similar phenomena were observed by Sedgwick along the edges of intruded basalt among the Carboniferous limestones and shales of High Teesdale.[2]

Among localities where the development of new minerals in proximity to eruptive rock has taken place on the most extensive scale, none have been more frequently or carefully described than some in the group of mountains lying to the east and south-east of Botzen, in the Tyrol (Monzoni, Predazzo). Limestones of Lower Triassic (or Permian) age have there been invaded by masses of monzonite (a rock intermediate between syenite and diorite, sometimes containing much augite), granite, melaphyre, diabase, and orthoclase porphyry. They have become coarsely-crystalline marble, portions of them being completely enveloped in the eruptive rock. But their most remarkable feature is that in them and in the eruptive rocks in contact with them many beautifully crystallized minerals have been developed, including garnet, idocrase, gehlenite, fassaïte, pistacite, spinel, anorthite, mica, magnetic iron, hæmatite, apatite, and serpentine. Some of these minerals occur chiefly or only in the eruptive masses, others more frequently in the limestone, which is marked by a lime-silicate hornstone zone along the junction. But these are all products of contact of the two kinds of rock. Layers of carbonates (calcite, also with brucite), alternate with laminæ and streaks of various silicates, in a manner strikingly similar to the arrangement found in limestones among areas of regional metamorphism, where no visible intrusive rock has influenced the phenomena.[3]

Production of foliation.—This is the most complete kind of metamorphic change, for not only are new minerals developed but the whole texture and structure of the rock are altered. Reference has been already (p. 541 *seq.*) made to the striking manner in which foliation has been superinduced upon ordinary sedimentary rocks round large bosses of granite. The details of this change deserve careful consideration, for they possess a high importance in relation to any theory of metamorphism.

A classical region for the study of this kind of alteration is in the Harz, where, round the granite masses of the Brocken and Ramberg, the Devonian and older Palæozoic rocks are altered into various flinty slates and schists which form a ring round the eruptive rock. Dykes and other masses of a crystalline diabase have likewise been erupted through the greywackes and shales, which in contact and for a varying distance beyond have been converted into hard siliceous bands (hornstone) and into various finely foliated masses (Fleckschiefer, Bandschiefer, Contact-schiefer, the spilosite and desmosite of Zincken). The

[1] *Cambridge Phil. Trans.* i. p. 402.

[2] *Op. cit.* ii. p. 175.

[3] On the Monzoni region, see Doelter, *Jahrb. Geol. Reichsanstalt.* 1875, p. 207, where a bibliography of the locality up to the date of publication will be found. Since 1875 other papers have appeared, of which the following dealing with the phenomena of contact-metamorphism may be mentioned. G. vom Rath, *Z. Deutsch. Geol. Ges.* 1875, p. 343. Lemberg, *Op. cit.* 1877, p. 457.

limestones have their carbon dioxide replaced by silica in a broad zone of lime-silicate along the contact.[1]

In the Christiania district of southern Norway instructive illustrations of the metamorphism of sedimentary rocks round eruptive granite have long been known. Kjerulf has shown that each lithological zone of the Silurian formations as it approaches the granite of that district assumes its own distinctive kind of metamorphism. The limestones become marble, with crystals of tremolite and idocrase. The calcareous and marly shales are changed into hard, almost jaspery, shales or slates; the cement-stone nodules in the shales appear as masses of garnet; the sandy strata become hard siliceous schists (Hälleflinta, jasper, hornstone) or quartzite; the non-calcareous black clay-slates are converted into chiastolite-schists, or graphitic schists, but often show to the eye only trifling alteration. Other shaly beds have assumed a fine glimmering appearance; and in the calcareous sandstone, biotite has been developed. In spite of the metamorphism, however, neither fossils nor stratification have been quite obliterated from the altered rocks. From all the stratigraphical zones fossils have been found in the altered belt, so that the true position of the metamorphosed rocks admits of no doubt.[2]

Round the granite bosses of Devon and Cornwall, Devonian and Lower Carboniferous strata have undergone similar metamorphism.[3] In the lake district of the north of England excellent examples of the phenomena of contact may be observed round the granite of Skiddaw. The alteration here extends for a distance of two or three miles, from the central mass of granite. The slate where unaltered is a bluish-grey cleaved rock, weathering into small flakes and pencil-like fragments. Traced towards the granite, it first shows faint spots, which increase in number and size until they assume the form of chiastolite crystals, with which the slate is now abundantly crowded. The zone of this andalusite-schist seldom exceeds a quarter of a mile in breadth. Still closer to the granite a second stage of metamorphism is marked by the development of a general schistose character, the rock becoming more massive and less cleaved, the cleavage planes being replaced by an incipient foliation due to the development of abundant dark little rectangular or oblong spots, probably imperfectly crystallized chiastolite, this mineral, as well as andalusite, occurring also in large crystals, together with minute flakes of mica (spotted schist, knotenschiefer). A third and final stage is reached when, by the increase of the mica and quartz-grains, the rock passes into mica-schist—a light or bluish-grey rock, with wonderfully contorted foliation, which is developed close to the granite, there being always a sharp line of demarcation between the mica-schist and the granite.[4]

Farther north in the south-western counties of Scotland several large masses of fine-grained granite rise through the Lower Silurian greywacke and shale, which, around the granite for a variable distance of a few hundred yards to nearly two miles, have undergone great alteration.

[1] Zincken, *Karsten und v. Dechen. Archiv.* v. p. 345; xix. p. 583. Fuchs, *N. Jahrb.* 1862, pp. 769, 929. K. A. Lossen, *Z. Deutsch. Geol. Ges.* xxi. p. 291; xxiv. p. 701. Kayser, *Op. cit.* xxii. p. 103. The memoirs of Lossen form some of the most important contributions to our knowledge of the phenomena of metamorphism.

[2] Kjerulf, "Geologie Norwegens," 1880, p. 78.

[3] De la Beche, "Geology of Devon and Cornwall," *Geol. Surv. Mem.* i. 1839.

[4] J. C. Ward, *Q. Journ. Geol. Soc.* xxxii. (1876), p. 1.

These strata are ranged in steep anticlinal and synclinal folds which run across the south of Scotland in a general north-east and south-west direction. It is observable that this normal strike continues, with little modification, up to the granite, which thus has replaced an equivalent area of sedimentary rock (see p. 542). The coarser arenaceous beds, as they approach the granite, are changed into quartz-rock, the thin siliceous shales into Lydian-stone, the black anthracitic graptolite-shales into a compact mass charged with pyrites, and breaking into large rough blocks. Strata wherein felspar-grains abound have been altered to a greater distance than the more siliceous beds, and show a gradation through spotted schists, with an increasing development of mica and foliation, until along the edge of the granite they become true mica-schist and even a fine kind of gneiss.[1]

Closely analogous to these examples are those described by Fuchs[2] from the French Pyrenees, and by Rosenbusch[3] from the Eastern Vosges. In the former case the metamorphism of clay-slate is traced through spotted schists (Frucht-, chiastolite-, and andalusite-schists) into mica-schist and gneiss. In the latter a zone of alteration is shown to surround the granite boss of Barr-Andlau. The unaltered clay-slates are grey, brown, violet, or black, thinly fissile, here and there curved, crumpled, and crowded with kernels and strings of quartz. Traced towards the granite, they present an increasingly pronounced metamorphism. First they assume a spotted appearance, owing to the development of small dark points and knots, which increase in size and number towards the granite, while the ground-mass remains unaltered (Knotenschiefer, Fruchtschiefer). The ground-mass of the slate then becomes lighter in colour, harder, and more crystalline in appearance, while flakes of mica and quartz-grains make their appearance. The knots, now broken up, rather increase than diminish in size; the hardness of the rock rapidly increases, and the fissile structure becomes unrecognizable on a fresh fracture, though observable on a weathered surface. Still nearer the granite, the knot-like concretions disappear from the rock, which then has become an entirely crystalline mass, in which, with the lens, small flakes of mica and grains of quartz can be seen, and which under the microscope appears as a thoroughly crystalline aggregate of andalusite, quartz, and mica. The proportions of the ingredients vary, but the andalusite and quartz usually greatly preponderate (andalusite-schist). Chemical analysis shows that the unaltered clay-slate and the crystalline andalusite-schist next the granite consist essentially of similar chemical materials, and that "probably the metamorphism has not taken place by the addition or subtraction of matter, but by another and still unknown process of molecular transposition."[4] In some cases boric acid has been supplied to the schists at the contact.[5]

[1] J. Horne, *Mem. Geol. Survey, Scotland*, Explanation of Sheet 9, p. 22. The fine "gneiss" found as a contact product round the granite of Devon and Cornwall was termed "cornubianite" by Boase—a name which Naumann has proposed to devote to this kind of rock. *Geol.* i. 548.

[2] *N. Jahrb.* 1870, p. 742.

[3] *Op. cit.* 1875, p. 849. "Die Steigerschiefer und ihre Contact-Zone," Strassburg, 1877. Unger, *N. Jahrb.* 1876, p. 785.

[4] Unger, *Op. cit.* p. 806.

[5] Rosenbusch, "Die Steigerschiefer," &c., p. 257.

An important paper upon the contact phenomena of the granite of Albany, New Hampshire, has been published by Mr. G. W. Hawes.[1] His analyses indicate a systematic and progressive series of changes in the schists as they approach the granite. The rocks are dehydrated, boric and silicic acids have been added to them, and there appears to have been also an infusion of alkali directly on the contact. He regards the schists as having been impregnated by very hot vapours and solutions emanating from the granite.

In Brittany Lower Silurian slaty rocks, where they approach masses of eruptive granite, assume a schistose character and contain large crystals of chiastolite, among which, in the same pieces of stone, specimens of brachiopods and trilobites may be seen.[2]

Summary of facts.—The foregoing examples of the alteration superinduced upon stratified rocks in proximity to granite or other eruptive masses might be largely increased; but they may suffice to establish the following deductions in regard to contact metamorphism.

1. Groups of ordinary sedimentary strata (sandstones, shales, limestones, &c.), where they have been pierced by granite or other plutonic rock, have undergone an internal change, whereby their usual lithological characters have been partially or wholly obliterated.

2. The distance to which this change extends varies within wide limits, being in some cases scarcely traceable for a hundred yards, in others continuing for two miles or more. The subterranean surface of the plutonic rock, however, being unknown, it may frequently lie nearer the surface of the ground than might be supposed. Detached minor areas of metamorphism may thus be connected with eruptive bosses which have not yet been laid bare by denudation.

3. As the alteration increases in intensity with greater proximity to the plutonic rock, it must be regarded as a result of the protrusion of that rock. But there occur exceptional areas or bands which have undergone a minor degree of change even in the midst of highly altered portions.

4. The character of the metamorphism depends fundamentally upon the composition and texture of the rock on which it has been effected. Sandstones have been changed into quartzite; siliceous schists into hornstone, Lydian-stone, &c.; clay-slates into spotted schists, chiastolite-schists, mica-schists, &c.; argillaceous greywacke and greywacke-slate into "knotenschiefer," mica-slate, and gneiss. Alternations of distinct kinds of sedimentary strata, such as slate and sandstone, are represented by distinct alternating metamorphic bands, such as quartzite and mica-schist.

5. In some cases the transformation of a thoroughly clastic rock (clay-slate, greywacke, greywacke-slate or flagstone) into a completely crystalline one (andalusite-schist, mica-schist, gneiss) has

[1] *Amer. Journ. Sci.* xxi. (January 1881), p. 21.
[2] Boblaye, *Comptes rendus*, 1838, p. 186; *Bull. Soc. Géol. France*, x. p. 227.

been effected with little or no alteration of the ultimate chemical composition of the mass. In other cases a perceptible alteration in the proportions of the chemical ingredients is traceable.[1] The development of a crystalline structure can be traced through intermediate stages from ordinary sedimentary rock to thoroughly foliated schist, remains of fossils being still observable after considerable progress has been made towards the completion of a crystalline rearrangement.

6. Not only does the crystalline character increase towards the limit of contact with the eruptive rock, but it is accompanied with a progressive development of foliation, the minerals, more especially the mica, crystallizing in folia parallel either with the original stratification of the clastic mass or with the cleavage surfaces should these be its dominant divisional planes.[2] Along the line of contact with granite the foliation is sometimes excessively crumpled or puckered, while here and there the foliated structure disappears and the rock assumes a lithological character closely approximating to that of granite.

7. The phenomena now described evidently point to the heat of eruptive rock as their prime cause. Mere dry heat, however, would probably have been ineffective for the production of the changes observed. It was accompanied by the co-operation of water, either already present interstitially in the sedimentary rocks or supplied to them from the eruptive masses. From experimental researches it is known that at a dull red heat in presence of water, important mineralogical transformations take place (*ante*, p. 300). There is reason to believe that by a reaction of this nature the phenomena of contact metamorphism were produced.

§ III.—Regional (Normal) Metamorphism.

From the phenomena of metamorphism round a central boss of eruptive rock we now pass to the consideration of cases where the metamorphism has affected wide areas without visible relation to eruptive matter. It is clear that only those examples are here admissible in evidence where there is distinct proof that the crystalline and foliated character passes into that of ordinary stratified materials, or where the rocks can be shown to be the equivalents of what are elsewhere ordinary unaltered masses.

At the outset it must be observed that a feeble but distinct trace of metamorphism is indicated by abundant veins of quartz and calcite which tell of a copious penetration by water charged with

[1] This is specially noticeable in the proportion of silica, which is sometimes found to be largely increased in the altered zone, either by an absolute addition of this acid, or by solution and removal of some of the bases. See Kayser, *Z. Deutsch. Geol. Ges.* xxii. p. 153.

[2] In the south of Scotland the foliation round the granite bosses is coincident with stratification; round Skiddaw, with cleavage.

mineral solutions. The plentiful diffusion of crystalline microliths in some clay-slates and even of recognizable microscopic crystals (garnet, &c.), with the retention of the ordinary characters and even fossil contents of clastic rocks, points to a more pronounced change, viz. the initiation of a general crystalline rearrangement, apart from the mere intrusion of eruptive matter. All that is known of the probable origin of these minerals negatives the supposition that they could have been formed in the original sediment of the sea bottom on which the organisms entombed in the deposits lived and died. For their production a temperature and a chemical composition of the water would seem to have been required such as must have been inimical to the co-existence in the same water of such highly organized forms of life as brachiopods and trilobites. Two regions may be cited here as affording proof of an extensive conversion of ordinary sedimentary strata of Palæozoic age into crystalline schists —the Highlands of Scotland and the Green Mountains of New England.

Evidence from the Scottish Highlands.—In geological structure Scotland presents three parallel zones, which cross the island from south-west to north-east. The southernmost of these consists chiefly of greywacke, grit, and shale, with some thick lenticular seams of limestone in the south-western part of the area. These rocks have yielded an abundant suite of organic remains, which prove them to be of Lower Silurian age. They have been extensively plicated into innumerable anticlinal and synclinal folds, often sharp and steep, not infrequently reversed (p. 518). The general persistent direction of the axes of those folds is N.E. and S.W., and as the tops of the arches have been greatly denuded, the Silurian belt appears to be made up of highly-inclined and even vertical strata. The central zone of the country, consisting of Old Red Sandstone, Carboniferous, and Permian formations, with abundant associated volcanic rocks, extends as a band about fifty miles broad, separating the Silurian uplands of the southern zone from the Highlands. The last-named region, occupying more than half of the whole country, consists mainly of crystalline schists with bosses of granite, porphyry, &c. These rocks stretch through four degrees of latitude, and four and a half of longitude, and must cover an area of not less than 16,000 square miles at the surface, but as they sink beneath later formations, and as they are prolonged into Ireland, their total area must be still more extensive. It was formerly believed that the crystalline schists of Scotland belonged to the early geological period in which such rocks were supposed to have been everywhere formed. Murchison, however, found the key to their structure, and proved them to be mainly of Lower Silurian age—the metamorphosed equivalents of the scarcely altered Lower Silurian strata in the southern zone of the kingdom.

The oldest rock of the whole region (*a*, Fig. 300) is a remarkably coarse crystalline gneiss seen in Sutherland and Ross, the two north-westerly counties of Scotland. It will be described in the section on Archæan rocks in Book VI. It is unconformably overlaid by nearly flat brownish-red (Cambrian) sandstones, conglomerates and breccias (*b*) which in turn are surmounted unconformably by inclined beds of quartzite and lime-

stone (*c*) dipping below a series of quartz-schists and micaceous flagstones or flaggy mica-schists (*d*). This order of succession is visible in many magnificent natural sections for a distance of ninety miles. The Lower Silurian age of these rocks is fixed by the occurrence of recognizable fossils in the lower parts of the series. The basement quartzite is full of annelide-burrows; the limestone has yielded *Maclurea*, *Murchisonia*, *Ophileta*, *Pleurotomaria*, *Orthis*, *Orthoceras*, and *Piloceras;* the shales are crowded with carbonaceous fucoid-like casts. On the whole, these fossiliferous strata are not much altered, but as the fissile series overlying them is traced eastwards, it is found to assume a more schistose character. The original stratification remains indeed quite distinct; bands of more sandy nature alternating with others of a more argillaceous composition, as sandstones and shales do elsewhere. Some of the strata are made up of water-worn pebbles of quartz, &c., in a schistose matrix. Even the false bedding of the sandy beds can readily be detected. With these evidences of an original clastic character, there is noticeable a fine foliation produced by the development chiefly of minute folia of mica in the planes of deposit. So long as the strata retain their gentle easterly inclination this foliation remains feeble and with little variation. But after passing across several thousand feet of these little altered strata, we find that they rapidly undergo a series of plications, after

Fig. 300.—Diagram of the Order of Succession among the Crystalline-schists of Scotland.

which their angle of inclination remains high for a long distance, as they are thrown into numerous steep arches and troughs (*e*).

With this change from a gentle and scarcely disturbed succession to a highly plicated and crumpled condition, there is an accompanying and proportionately rapid increase in crystalline character. The rocks become thoroughly foliated mica-schists and fine gneisses, containing porphyritic crystals of orthoclase and garnet with concretions and veins of quartz. The rest of the Highlands to the east and south is overspread by a continuation of these same rocks. By numerous anticlinal and synclinal foldings quartzites and limestones are brought to the surface, but are almost always more crystalline than the rocks of the north-west. The crystalline condition, however, is by no means uniform. In certain regions argillaceous beds occur which are rather shales than schists, so little have they been changed. These beds elsewhere pass into spotted schists and andulusite-schists. The limestones often occur, as they do in Sutherlandshire, in association with white quartzites; sometimes they are grey, granular, and finely crystalline, sometimes they appear as white marble containing garnet, idocrase, tremolite, zoisite, and many other silicates. The alteration has thus been remarkably unequal over the whole region, and has reached the maximum development sporadically, particularly where the strata exhibit proofs of intense crumpling. It is deserving of remark that the rocks along the southern margin of the Highlands are for the most part comparatively little altered, and that they dip towards the

mountains, becoming more highly foliated and crystalline as they recede from the lowlands.

Numerous bosses of granite and porphyries occur among the crystalline schists. But the metamorphism is not specially connected with their protrusion, though usually in their vicinity the schists attain a more largely crystalline condition. Here and there, indeed, a gradation can be traced through gneiss into granite. This is more particularly observable in districts where veins, whether of intrusion or of segregation, are abundant. Remarkable examples may be observed in Eastern Sutherland (Lairg), and on the coast-line south of Aberdeen, where the gneiss loses its schistose structure, and passes into granite, which lies in beds intercalated in the gneiss, and in which may be seen scattered patches of gneiss still retaining foliation. On the other hand, some of the masses of granite assume here and there a perfectly gneissose structure, as at the large granite quarries near Aberdeen, where this structure may be specially observed in connection with segregation veins (Fig. 284).

In the Scottish Highlands, therefore, it can be proved that rocks containing Lower Silurian fossils are overlaid by thousands of feet of crystalline schists, quartzites, and limestones. That these overlying masses are not original chemical precipitates may be concluded on the following grounds. 1st, They demonstrably overlie fossiliferous Lower Silurian rocks. Strata of corresponding geological age occur to a depth of many thousand feet in the South of Scotland, within sight of the crystalline rocks of the Highlands. It cannot be supposed that on the same sea-floor, and within the same limited area, mechanical sediments alone accumulated in one tract, while only a few miles distant chemical precipitates—gneisses, garnetiferous schists, &c.,—were laid down, in each case to a depth of thousands of feet. 2nd, The crystalline schists of the Highlands in their less altered parts present the closest resemblance to the ordinary greywackes, grits, and shales of the Lower Silurian series of the South of Scotland. Moreover, the altered rocks round the granite bosses in this latter area cannot be distinguished from similar rocks in the regional metamorphic area of the Highlands. 3rd, Throughout all parts of the Highland region traces of an original fragmental or clastic origin can be detected among the schistose rocks. Zones of fine grit full of well-rounded fragments of quartz, felspar, or other ingredient abound among the schists. Bands of coarse conglomerate likewise occur on different horizons, the pebbles (granite, gneiss, &c.) being enveloped in a schistose matrix. Microscopic investigation likewise reveals, even among the crystalline mica-schists, traces of the original water-worn granules of quartz in the sandy mud out of which the rocks have been formed. The conclusion is thus reached that in the Highlands of Scotland there is a mass of rocks originally composed mainly of ordinary mechanical sediments which have assumed in various degrees a crystalline condition over a region which, including the north of Ireland, must cover more than 20,000 square miles.

Green Mountains of New England.—In this region a similar series of changes has been effected. The Lower Silurian strata, which to the north in Vermont are comparatively little changed, become increasingly altered as they are traced southwards into New York Island. They are thrown into sharp folds, and even inverted, the direction of plication being generally N.N.E. and S.S.W. This disturbance has been

accompanied by a marked crystallization. The limestones have become marbles, the sandy beds quartzites, and the other strata have assumed the character of slate, mica-schist, chlorite-schist, and gneiss, among which hornblendic, augitic, hypersthenic, and chrysolitic zones occur. The geological horizon of these rocks is shown by the discovery in them at various localities of fossils belonging to the Trenton and Hudson River subdivision of the Lower Silurian system of eastern North America. The rocks have been ridged up and altered along a belt of country lying to the east of the Hudson and extending north into Canada.[1]

Other examples might be cited. A long belt of regional metamorphism extends through the Ardennes, and instructive areas occur in the Harz and in Greece. Some parts of the Triassic formations of the Sierra Nevada of Western North America have been found by Whitney in the condition of serpentine and mica-schist; while on the Coast Range of California he has met with similar metamorphism of the Cretaceous series. It is probable that such alterations have repeatedly occurred in successive geological periods over the surface of the globe.

From the evidence of such examples, the conclusion may be drawn that there are extensive regions where ordinary sedimentary strata have been plicated, crumpled, and foliated, so as to assume the character of true crystalline schists. This change is precisely similar in its stages to that which may be traced in local metamorphism round bosses of granite. It is connected with, and proportional to, mechanical disturbance of the strata. It is unequal in extent, even over limited areas, being apt to attain sporadically a maximum development, particularly in the areas of greatest plication. Even in the midst of the metamorphosed tracts, bands of comparatively unchanged rock may be traced, the true clastic origin of which cannot be disputed. The process was not everywhere uniform, partly, no doubt, because of the varying composition of the rocks subjected to its operation, and partly because it really was more actively induced in areas of greater disturbance.

From the evidence furnished by local metamorphism, there can be little hesitation in regarding the bedding of the crystalline rocks in a tract of regional metamorphism as generally representing original layers of deposit. In some cases, however, the foliation may represent cleavage, as pointed out by Sedgwick and Darwin. So far, indeed, as a rock continued homogeneous in chemical composition and general texture, foliation might be induced along any dominant divisional planes. If these planes were those of cleavage, the resultant foliation might not appreciably differ from cleavage along original bedding planes. But it may be doubted whether a cleavage foliation could run without sensible and even very serious interruptions over wide areas. For, in the first place, in most large masses of sedimen-

[1] See Dana, *Amer. Journ. Sci.* xiii. xiv. xvii. The identification of the so-called Taconic schists of New England with altered Lower Silurian rocks has been called in question by Sterry Hunt, but the stratigraphical evidence collected by A. Wing, Dana, and others, and the testimony of the fossils collected by Dana, Dwight, &c., have sustained it. In the Punjab a series of gneisses and schists overlies infra-Triassic rocks. Wynne, *Geog. Mag.* 1880, p. 314.

tary matter we encounter alternations of different kinds of sediment, which could not but produce distinct kinds of rock under the influence of metamorphic change. In the second place, cleavage depends for its perfection and continuity on the fineness of grain of the rock through which it runs. While exceedingly perfect in a mass of argillaceous strata, it becomes feebler or even dies out in a coarse sandy or gritty rock. Hence, where foliation coincides with cleavage over large tracts, there will almost certainly be bands, more or less distinct, coincident with the original stratification, and running oblique to the general foliation, like bedding and cleavage, save where these two kinds of structure may happen to coalesce.

In a region of intense metamorphism the foliation of the schists becomes here and there somewhat indefinite, until, disappearing altogether, it gives place to a thoroughly granitic character. Between gneiss and granite there is no difference in mineralogical composition; in the one rock the minerals are arranged in folia, in the other they have no definite arrangement. Gneiss might be called a foliated granite; granite might be termed a non-foliated gneiss, and, indeed, the two rocks may sometimes be observed to graduate into each other. It has been naturally concluded that such granite is the ultimate stage of metamorphism.

There is thus nothing improbable in the idea that the same mineral particles may have gone through many successive cycles of change. We may suppose them to have been originally part of a granite mass, and to have been subsequently exposed at the surface by enormous denudation. Worn away from their parent granite they would be washed down with other particles, and spread out under water as parts of sandy or muddy deposits. Buried under a gradual accumulation of sedimentary material thousands of feet in thickness, they might be depressed deep beneath the surface, and be thus brought within the influence of metamorphism. Gradually recomposed, crystallized, and converted into schistose rock, they might be eventually reduced to a soft or pasty condition and protruded into some of the overlying less metamorphosed masses in the form of granite veins. Or we may conceive, that a communication was opened between the granite thus produced and the surface, and that the original mineral particles, whose vicissitudes we have been tracing, were finally erupted to the surface as part of a stream of lava (p. 545).

Possible Metamorphism of Igneous Rocks.—In most large tracts of foliated rocks there occur masses less distinctly foliated or quite granitoid in texture, formed mainly of hornblende or of that mineral in combination with others. Zones or bosses of hornblende-rock and hornblende-schist frequently appear among gneiss and mica-schist. Varieties of quartz-porphyry occur in a similar way. Bands of fine unctuous chloritic or hydro-mica schists may also often be traced. It is not easy to understand how such rocks, at least those containing a large percentage of magnesia, could be produced by the metamorphism of ordinary sediment,

unless we conceive the sediment to have been of the nature of the magnesian clays (sepiolites) of the Paris basin. It is possible, however, that some of these magnesian rocks were originally of igneous origin, either erupted at the surface or intrusively injected among the surrounding rocks previous to metamorphism. Such mineral masses as varieties of syenite and diorite, rich in hornblende or other magnesian silicates, might have been the origin of many of the rocks here referred to. Fine schists consisting mainly of hydrous magnesian silicates may have been at first tuffs associated with the lava-form masses.

§ IV.—The Archæan Crystalline Schists.

We now finally advance to the consideration of those schistose rocks which underlie the oldest fossiliferous and sedimentary formations. On the whole they present the closest resemblance to tracts of regional metamorphosed rocks, though, as a rule, more coarsely crystalline, containing more massive bands of gneiss, hornblende-rock, &c., and being more intricately veined with granite, pegmatite, and allied crystalline masses. The most natural inference to be drawn as to their origin is obviously to regard them as derived from the metamorphism of ordinary sedimentary rocks. This conclusion has been adopted by the majority of geologists. The Archæan crystalline-schists are assumed to be of metamorphic origin, and indeed the phrase "metamorphic rocks" is often used as a synonym for these oldest crystalline masses. But though their close resemblance to the products of regional metamorphism may justify the inference usually drawn, it does not amount to a proof of absolute identity of origin.

The difficulty of explaining some of the transformations which on the theory of metamorphism must have taken place, has led to another explanation. Some writers, justly repudiating the exaggerated views of those who have sought by metamorphic (metasomatic) processes to derive the most utterly different rocks from each other (for example, limestone from gneiss and granite, granite and gneiss from limestone, talc from granite, &c.), have insisted that the cystalline schists, in common with many pyroxenic and hornblendic rocks (diabases, diorites, &c.), as well as masses in which serpentine, talc, chlorite, and epidote are prevailing minerals, have been deposited "for the most part as chemically-formed sediments or precipitates, and that the subsequent changes have been simply molecular, or at most confined in certain cases to reactions between the mingled elements of the sediments, with the elimination of water and carbonic acid." To support this view, it is necessary to suppose that the rocks in question were formed during a period of the earth's history when the ocean had a considerably different relative proportion of mineral substances dissolved in its (then probably much warmer) waters; they are consequently assigned to a very early geological period, anterior indeed to what are usually

termed the Palæozoic ages. It becomes further needful to discredit the belief that any gneiss or schist can belong to one of the later stages of the geological record, except doubtfully and merely locally. The more thorough-going advocates of the pristine, "azoic," or "eozoic," date, and original chemical deposition of the so-called "metamorphic" rocks, do not hesitate to take this step, and endeavour, by ingenious explanations, to show that the majority of geologists have mistaken the geological structure of the districts where these rocks have been supposed to be metamorphosed equivalents of what elsewhere are Palæozoic, Secondary, or Tertiary strata.[1] They even go so far as to assert that by mere mineral characters the crystalline rocks of contemporaneous periods can be identified all over the world. They assume that in the supposed chemical precipitation, the same general order has been followed everywhere over the floor of the ocean. Consequently a few hand specimens of the crystalline rocks of a country are enough in their eyes to determine the geological position of these formations. If geologists have discovered that the actual sequence of rocks is quite different, so much the worse for the geologists.

In conclusion, the mode of origin of the Archæan crystalline schists is a problem which cannot yet be satisfactorily solved. On the one hand it must be conceded that during the very ancient periods in which they were deposited, the composition of the waters of the ocean may have been very unlike what it afterwards became, and there may have been chemical precipitates on the sea-floor, such as could not have been formed in later and cooler times when life had already appeared on the earth. On the other hand, the striking resemblance in structure and composition between the crystalline schists and rocks which can be proved to be the metamorphosed equivalents of ordinary sedimentary strata renders it highly probable that these ancient schists, whatever the circumstances of their original formation, have undergone plication, crumpling, and metamorphism analogous to that of younger formations in areas of regional metamorphism.[2]

PART IX.—ORE DEPOSITS.[3]

Metallic ores and other minerals that are extracted for their economic value occur in certain well-marked forms which have been

[1] See Sterry Hunt's *Chemical Essays*, p. 382 *sq.*

[2] Besides the works already cited on Metamorphism the student may consult the following: Delesse, *Mem. Savans Etrangers*, xvii. Paris, 1862, pp. 127–222; *Ann. des Mines*, xii. (1857); xiii. (1858); Daubrée, *Ann. des Mines*, 5th series, xvi. p. 155; Bischof, "Chemical Geology," chap. xlviii.; J. Roth, *Abhandlungen Akad. Berlin*, 1871; 1880; Gümbel, "Ostbayerische Grenzgebirge," 1868; H. Credner, *Zeitsch. Gesammt. Naturwiss.* xxxii. (1868), p. 353; *N. Jahrb.* 1870, p. 970.

[3] The following works on ores and mining may be consulted: B. von Cotta, "Die Lehre von Erzlagerstätten," 1859–61; A. von Groddeck, "Die Lehre von den Lagerstätten der Erze," 1879; W. Forster's "Treatise on a Section of the Strata from Newcastle-on-Tyne to Cross Fell;" W. Wallace's "Laws which regulate the deposition of

variously classified; but for the purposes of the geological student it is most convenient to consider them from the point of view of geological structure and history. Thus arranged, they naturally group themselves into three great series: 1st, those contemporaneously deposited among stratified formations; 2nd, those contemporaneously formed with the other ingredients of crystalline (massive and schistose) rocks; 3rd, those subsequently introduced by infiltration or otherwise into fissures, caverns, or other spaces of any kind of rock.

1. Contemporaneous ores of stratified rocks have been deposited in water together with the sandstones, limestones, or other strata among which they lie. They belong to the stratified type of geological structure described in Part I. (p. 474). They occur in beds varying from mere films up to masses of great thickness. In some cases they retain the same average thickness for long distances, in others they swell out or die away rapidly, or occur in scattered concretions. Among the more frequent ores of this group are limonite and siderite. Abundant examples are supplied by the bog-iron deposits now forming, and by the bands of brown-iron ore, red-iron ore, and clay-ironstone associated with Carboniferous and other formations. Occasionally the ore has been finely disseminated through the strata at the time of their deposit, as in the cupriferous slates of the German Zechstein. Organic remains are commonly associated with ores of this type (*ante*, p. 174).

2. Contemporaneous ores of crystalline rocks are exemplified by the beds of iron-ore, pyrites, &c., that so frequently occur intercalcated among the crystalline schists (*ante*, pp. 118, 569). They lie as massive sheets or thin partings, and usually present a conspicuously lenticular character. That they were formed contemporaneously with the layers of quartz, mica, felspar, hornblende, or other minerals among which they lie, may usually be inferred with considerable certainty, though cases not infrequently arise where it is difficult or impossible to draw any line between this type and that of true subsequently-formed veins. Besides these lenticular ores of the crystalline schists, the massive rocks also contain contemporaneously crystallized ores. The diffused magnetite and titaniferous iron of the basalts, diabases, &c., are familiar illustrations. Large included masses of these and other ores are sometimes available for mining (*ante*, pp. 64, 145, 147).

3. Subsequently introduced ores are distinguished by the contrast between their contents and structure and those of the rocks through which they pass. They have been deposited, subsequent to the consolidation of these rocks, in cavities previously opened for

Lead Ores," 1861. Numerous valuable papers by the late J. W. Henwood and others are to be found in the *Trans. Roy. Geol. Soc. Cornwall*. It is understood that a systematic English treatise on the subject may be expected from Mr. J. A. Phillips and Mr. H. Bauerman.

their reception. In certain rocks (limestones, dolomites, &c.) intricate channels and large irregular caverns have been dissolved out by the solvent action of underground water; in other cases fissures have been formed by fracture, or the rocks, exposed to great compression, have been puckered up or torn asunder, so that irregular spaces have been opened in them. Metallic ores and crystalline minerals introduced by infiltration, sublimation or otherwise, into the cavities formed in any of these ways, may be grouped according to the shape of the cavity into veins or lodes, which have filled up vertical or highly inclined fissures, and stocks which are indefinite aggregations often found occupying the place of subterranean cavities.

The first two types of ore-deposits do not require special treatment here. The stratified type has the usual character of sedimentary formations (Book IV. Part I.); the crystalline type forms part of the structure of schistose and massive rocks (Book II. Part II. § vi. 2 and 3); the third type, however, from its economic importance and its geological interest, merits some more detailed notice.

§ 1. Mineral Veins or Lodes.

A mineral vein consists of one or more minerals deposited within a fissure of the earth's crust. Such fissures being usually highly inclined or vertical, so also are mineral veins. Cases occur, however, among crystalline massive rocks, and still more frequently among limestones, where the introduction of mineral matter has taken place along gently inclined or even horizontal planes, such as those of stratification, and the veins then look like interstratified beds. Mineral veins are composed of masses or layers of simple minerals or metallic ores alternating, or more irregularly intermingled with each other, distinct from the surrounding rock, and evidently the result of separate deposition. They are in no respect to be confounded with veins of rock injected in a molten condition from below, or segregated from a surrounding pasty magma into cracks in its mass.

Variations in breadth.—Mineral veins vary in breadth from a mere paper-like film up to a great wall of rock 150 feet wide or more. The simplest kinds are the threads or strings of calcite and quartz so frequently to be observed among the more ancient and especially more or less altered rocks. These may be seen running in parallel lines or branching into an intricate network, sometimes uniting into thick branches and again rapidly thinning away. Considerable variations in breadth may be traced in the same vein. These may be accounted for either as due to unequal solution and removal of the walls of a fissure, as in the action of permeating water upon a calcareous rock; or to the irregular opening of a rent, or to a shift of the walls of a sinuous or irregularly defined fissure. In the last-named case the vein may be strikingly unequal in breadth, here and there nearly disappearing by the convergence of the walls and then rapidly swelling out and again diminishing.

How simply this irregularity may be accounted for, will be readily perceived by merely copying the line of such an uneven fissure on tracing paper and shifting the tracing along the line of the original. If, for example, the fissure be assumed to have the form shown at *ab*, in the first line (Fig. 301), a slight shifting of one side to the right, as

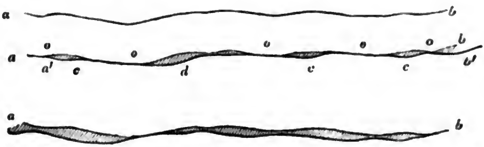


Fig. 301.—Widening of a Fissure by relative Shifting of its Side (*B.*).

at *a′ b′*, in the second line will allow the two opposite walls to touch at only the points *o o*, while open spaces will be left at *c c d*. A movement to the same extent in the reverse direction would give rise to a more continuously open fissure as in the third line. That shiftings of this nature have occurred to an enormous extent in the fissures filled with mineral veins is shown by the abundant slickensides (p. 504). The polished and striated walls have been coated with mineral matter, which has subsequently been similarly polished and grooved by a renewal of the slipping.

Structure and Contents.—A mineral vein may be either simple, that is, consisting entirely of one mineral, or compound,

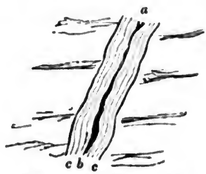


Fig. 302.—Section of a Fissure nearly filled with one Mineral (*c c*), but with a portion of the Fissure (*a b*) still open (*B.*).

consisting of several, and may or may not be metalliferous. The minerals are usually crystalline, but layers or irregular patches of soft decomposed earth, clay, &c., frequently accompany them. The non-metalliferous minerals are known as veinstones, the more crystalline being often also popularly classed as spars. The metal-bearing minerals are known as ores. The commonest veinstones are quartz, calcite, barytes, and fluorite. The ores are sometimes native metals, especially in the case of copper and gold; but for the most part are oxides, silicates, carbonates, sulphides, chlorides, or other combinations. Of the manner in which the contents of a mineral vein are disposed, the following are the chief varieties.

(1.) M a s s i v e.—Showing no definite arrangement of the contents. This structure is especially characteristic of veins consisting of a single mineral, as of calcite, quartz, or barytes. Some metalliferous ores (pyrites, limonite) likewise assume it.

(2.) B a n d e d, or in parallel (and usually duplicated) layers. In this common arrangement, each cheek (*a a*, Fig. 303) may be coated with a layer of the same material (*b b*), followed on the inside

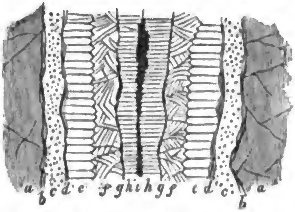


FIG. 303.—SECTION OF MINERAL VEIN WITH SYMMETRICAL DISPOSITION OF DUPLICATE LAYERS.

by another layer, *c c*, and so on to the centre, where the two opposite walls are finally united by the last zone of deposit (*i*). Even where each half of the vein is not strictly a duplicate of the other, the same parallelism of distinct layers may be traced.

(3.) B r e c c i a t e d, containing angular fragments of the surrounding rock (or "country,") cemented in a matrix of veinstones or ores. It may often be observed that these fragments are completely enclosed within the matrix of the vein, which must have been partially open and the matrix still in course of deposit when they were detached from the parent rock.

(4.) D r u s y, containing or made up of cavities lined with crystalline minerals. The central parts of veins frequently present this structure, particularly where the minerals have been deposited from each side towards the middle.

(5.) F i l a m e n t o u s, having the minerals disposed in thread-like veins; this is one of the commonest structures.

Metallic ores occur under a variety of forms in mineral veins. Sometimes they are disseminated in minute grains or fine threads (gold, pyrites), or gathered into irregular strings, branches, bunches, or leaf-like expansions (native copper), or disposed in layers alternating with the veinstones parallel with the walls of the vein (most metallic ores), or forming the whole of the vein (pyrites, and occasionally galena), or lining drusy cavities, both on a small scale and in large chambers (hæmatite, galena). Some ores are frequently found in association (galena and blende), or are noted for containing minute proportions of another metal (argentiferous galena, auriferous pyrites).

Successive in-filling of veins.—The symmetrical disposition

represented in Fig. 303 shows that the fissure had its two walls coated first with the layers *b b*. Thereafter the still open or subsequently widened cleft received a second layer (*c c*) on each face, and so on progressively until the whole was filled up or until only cavernous spaces (druses) lined with crystals were left. In such cases no evidence exists of any terrestrial movement during the process of successive deposition. The fissure may have been originally as wide as the present vein or may have been widened during the accumulation of mineral matter so gradually and gently as not to disturb the gathering layers. But in many instances, as above stated, proofs remain, of a series of disturbances whereby the formation of the vein was accelerated or interrupted. Thus at the Wheal Julia lode, Cornwall, the central zone (*e* in Fig. 304) is

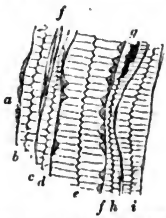


Fig. 304.—Section of Wheal Julia Lode, Cornwall, showing five successive openings of the same fissure (*B.*).

a f f, Copper-pyrites and Blende; *b d e, h, i*, Quartz in crystals pointing inwards: *e*, clay; *g*, empty space.

formed of quartz-crystals pointing as usual from the sides towards the centre of the vein, but it is only one of five similar zones, each of which marks an opening of the fissure and the subsequent closing of it by a deposit of mineral matter along the walls.[1] The occurrence of different layers on the two walls of a vein may sometimes indicate successive openings of the fissure. In Fig. 305 the fissure at one time

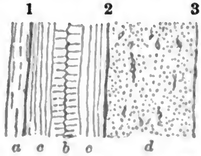


Fig. 305.—Section of part of a Lode, Godolphin Bridge, Cornwall (*B.*).

a, Quartz coating cheek of vein; *b*, Quartz Crystals pointing inward; *c*, Agatiform Silica; *d*, thick layer of Copper-pyrites.

no doubt extended no farther than between 1 and 2. Whether the band of copper pyrites had already filled up the fissure previous

[1] De la Beche, *Geol. Obs.* p. 698.

to the opening which allowed the deposit of the silica, or was introduced into a fissure opened between 2 and 3 after the deposit of the silica, is uncertain.[1]

The occurrence of rounded pebbles of slate, quartz, and granite in the lodes of Cornwall at depths of 600 feet from the surface, of gneiss in the vein at Joachimsthal at 1150 feet, and of Liassic land and fresh-water shells at 270 feet in veins traversing the Carboniferous Limestone of the Mendip Hills and South Wales, seems to indicate that fissures may remain sufficiently open to allow of the introduction of water-worn stones and terrestrial organisms from the surface even down to considerable depths.[2]

Connection of veins with faults and cross veins.—While any divisional planes in rocks may serve as the receptacle of mineral depositions, the largest and most continuous veins have for the most part been formed in lines of fault. These may be traced sometimes in a nearly straight course for many miles across a country, and as far downward as mining operations have been able to descend. Sometimes veins are themselves faulted and crossed by other veins. Like ordinary faults also, they are apt to split up at their terminations. These features are well exhibited in some of the mining districts of Cornwall (Fig. 306).

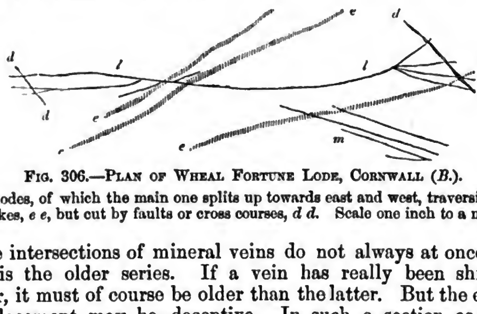


FIG. 306.—PLAN OF WHEAL FORTUNE LODE, CORNWALL (*B.*).
l, *l*, *m*, lodes, of which the main one splits up towards east and west, traversing elvan dykes, *e e*, but cut by faults or cross courses, *d d*. Scale one inch to a mile.

The intersections of mineral veins do not always at once betray which is the older series. If a vein has really been shifted by another, it must of course be older than the latter. But the evidence of displacement may be deceptive. In such a section as that in Fig. 307, for example, a cursory examination might suggest the inference that the vein *d e* must be later than the dyke or vein *a b* by which its course appears to have been shifted. Should more careful scrutiny, however, lead to the detection of the vein crossing the supposed later mass at *c*, it would be clear that this inference must be incorrect.[3] In mineral districts different series or systems of mineral veins can generally be traced, one crossing another, belonging to different periods, and not infrequently filled with

[1] De la Beche, *Op. cit.* p. 699.
[2] De la Beche, *Op. cit.* p. 696. Moore, *Q. J. Geol. Soc.* xxiii. 483; *Brit. Assoc.* 1869, p. 360.
[3] De la Beche, *Op. cit.* p. 657.

different ores and veinstones. In the south-west of England, for example, a series of fissures running N. and S., or N.N.W. and

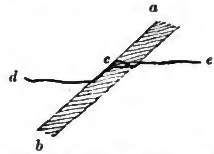


Fig. 307.—Deceptive shifting of a Vein (*B.*).

S.S.E., traverses another series, which runs in a more east and west direction (W.S.W. to E.N.E., or W.N.W. to E.S.E.). The latter (*c c*, ***d d***, Fig. 308) in Cornwall contain the chief copper and tin ores,

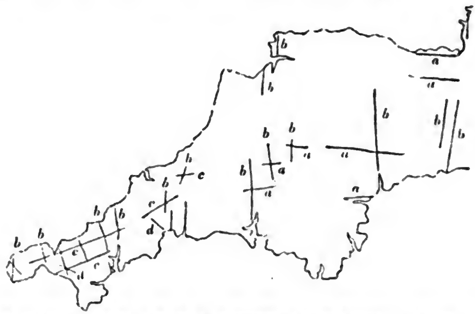


Fig. 308.—General Map of Fissures in the Mineral Tracts of S.W. England (*B.*).

while the cross-courses (*b b*) contain lead and iron. The east and west lodes in the west part of the region were formed before those which cross them, for they are shifted, and their contents are broken through by the latter. To the east, near Exeter, the east and west faults *a a* are later than the New Red Sandstone, and in Somerset than the Lias.[1]

Relation of contents of veins to surrounding rock.—It has long been familiar to miners that where a vein traverses various kinds of "country" it is often richer in ore when crossing or touching some rocks than others. In the north of England, for example, the galena is always most abundant in the limestone and scarcest in the shale, the veins in the Great Limestone (150 feet thick or less) having produced as much lead as all the rest of a mass of 2000 feet of strata put together. In Cornwall and Devon it has been observed

[1] De la Beche, *Op. cit.* p. 659.

that some lodes yield tin where they cross granite, and copper where they traverse slate; the same lode, as at Botallack, may cross three times from the one rock into the other, and each time the same change of metallic contents takes place. Some of the lodes which are poor in ore in the slate become rich as they cross an elvan (Fig. 309), or,

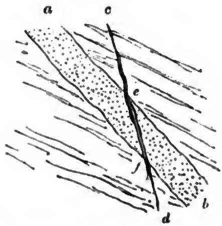


FIG. 309.—PLAN OF ELVAN DYKE (a b) TRAVERSED BY A METALLIC VEIN (c e f d), WHICH DIES OUT AS IT PASSES INTO THE SURROUNDING SLATE, WHEAL ALFRED, GUINEAR (*B.*).

on the other hand, the ore is so split up into strings in the elvan, as to be much less valuable than in the slate. Similar variations in the nature or amount of ores and veinstones with the character of the rocks traversed by mineral veins have been generally observed in mining districts, even among the most diverse geological formations.

Decomposition and recomposition in mineral veins.—It has been noticed that the "country" through which mineral veins run is often considerably decomposed. In Cornwall this is frequently very observable in the granite. Moreover, in most mineral veins there occur layers of clay, earth, or other soft friable loamy substances to which various mining names are given. In the south-west of England the great majority of the remarkable minerals of that district occur in those parts of the lodes where such soft earths abound. The veins evidently serve as channels for the circulation of water both upward and downward, and to this circulation the decay of some bands into mere clay or earth, and the recrystallization of part of their ingredients into rare or interesting minerals are to be ascribed.

§ 2. **Stocks and Stock-works.** (Stöcke, Stockwerke.)

The cavernous spaces dissolved out in some rocks, more especially in limestones and dolomites, may be of any indeterminate shape, and may be filled with one or more veinstones or ores, either in symmetrical zones following the outline of walls, floor, and roof, or in parallel and roughly horizontal bands (Fig. 310). Irregular metalliferous masses of this kind have long been known in Germany by the name of stocks (Stöcke) when of large size, smaller aggregations being

known as Butzen (cones) and Nester (tufts). The size of these indefinite accumulations of ore varies from mere nests up to masses 800 feet or more in one direction by 200 feet or more in another. Hæmatite, brown iron-ore, and galena not infrequently occur in this form in limestone, as in the "pockets" of hæmatite in the Carboniferous Limestone of Westmoreland. The "gash" or "rake"

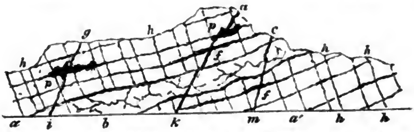


Fig. 310.—Section of Mineral deposits in Limestone, Derbyshire (*B.*).

a a a', Carboniferous Limestone with intercalated bed of pyroxenic lava or "toadstone" (*b*); *h h h h*, joints traversing the limestone, *i g*, *k d*, *m c*, veins traversing all the rocks and containing veinstones and ores; *f*, spaces between the beds enlarged by solution and filled with minerals or ores ("flat-works"); *p p*, large irregular cavernous spaces dissolved out of the rock and filled with minerals and ores.

veins of galena in the north of England occur in vertical joints of limestone which have been widened by solution, and are sometimes completely cut off underneath by the floor of shale or sandstone on which the limestone lies. Lenticular aggregations of ore and veinstone found in granite, as in the south-west of England, where they are known as Carbonas, cannot be due to the infilling of chambers dissolved by subterranean solution. They are usually connected with true fissure-veins; but their mode of origin is not well understood.

Stock-works are portions of the surrounding rock or "country" so charged with veins, nests, and impregnations of ore that they can be worked as metalliferous deposits. The tin stock-works of Cornwall and Saxony are good examples. Sometimes a succession of such stock-works may be observed in the same mine. Among the granites, elvans, and Devonian slates of Cornwall, tin-ore has segregated in rudely parallel zones or "floors." At Botallack, at the side of ordinary tin lodes, floors of tin-ore from six to twelve feet thick and from ten to forty feet broad occur.

Origin of mineral veins.—Various theories have been proposed to account for the infilling of mineral veins. Of these the most noteworthy are—(1) the theory of lateral segregation,—which teaches that the substances in the veins have been derived from the adjacent rocks by a process of leaching, or solution and redeposit; and (2) the theory of infilling from below,—according to which the minerals and ores were introduced dissolved in water or steam, or by sublimation, or by igneous fusion and injection.

The fact that the nature and amount of the minerals, and especially of the ores, in a vein so often vary with the nature of the surrounding rocks seems to show that these rocks have had a certain

influence on the precipitation of mineral matter in the fissures passing through them. But that this mineral matter came chiefly from below appears almost certain. The phenomena of the ascent of hot water in volcanic districts afford a close analogy to what has occurred in mineral veins. It is known that at the present time various minerals, including silica, both crystalline and calcedonic, and various metallic sulphides, are being deposited in fissures up which hot water rises.[1] At the same time it is conceivable that to some extent there may be a decomposition of the rocks on either side of a fissure, and that a portion of the mineral matter abstracted may be laid down in another form along the walls of the fissure, or, on the other hand, that the rocks on either side of the fissure may be permeated for some distance by the ascending waters, and that some of the mineral substances carried up in solution may be deposited in the pores and cavities of these rocks as well as in the fissure itself.[2]

PART X. UNCONFORMABILITY.

Where one series of rocks, whether of aqueous or igneous origin, has been laid down continuously and without disturbance upon another series, they are said to be *conformable*. Thus in Fig. 311 the sheets of conglomerate (*b b*) and clays and shales (*c d*), have succeeded each other in regular order, and exhibit a perfect conformability. They

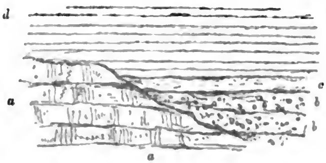


FIG. 311.—UNCONFORMABILITY AMONG HORIZONTAL STRATA. LIAS RESTING ON CARBONIFEROUS LIMESTONE, GLAMORGANSHIRE (*B.*).

overlap each other, however, each bed extending beyond the edge of that below it. As already explained (p. 495), this structure points to a gradual subsidence and enlargement of the area of deposit. But all these conformable beds repose against the older platform *a a*, with which they have no direct connection. That platform may consist of horizontal or inclined clastic strata, or contorted schists, or eruptive massive rocks. In any case there is a complete break between it and the overlying formation, the beds of which rest suc-

[1] See J. A. Phillips, *Q. J. Geol. Soc.* xxxv. p. 390.

[2] Henwood, *Address Roy. Inst. Cornwall*, 1871. J. A. Phillips, *Phil. Mag.* Nov. 1868, December 1871, July 1873, March 1874. J. S. Newberry, *School of Mines Quarterly*, New York, March 1880. J. A. Church, "The Comstock Lode," 4to. New York, 1879. Sterry Hunt, "Chemical and Geological Essays," 1875, p. 183. Brough Smyth's "Goldfields of Victoria," Melbourne, 1869.

cessively on different parts of the older mass. This relation is termed an unconformability. The upper conformable beds (*b c d*) are said to lie unconformably upon the lower (*a a*).

It is evident that this structure may occur in ordinary sedimentary, igneous, or metamorphic rocks, or between any two of these great series. It is most familiarly displayed among clastic formations, and can there be most satisfactorily studied, since the lines of bedding furnish a ready means of detecting differences of inclination and discordance of superposition. But even among igneous protrusions and in ancient metamorphic masses, distinct evidence of unconformability is not always difficult to trace. Wherever one series of rocks is found to rest upon a highly denuded surface of an older series, the junction is unconformable.[1] Hence, an uneven irregularly-worn platform below a succession of mutually conformable rocks is one of the most characteristic features of this kind of structure.

It has already been pointed out, that though conformable rocks may usually be presumed to have followed each other continuously without any great disturbance of geographical conditions, we cannot always be safe in such an inference. But an unconformability leaves no room to doubt that it marks a decided break in the continuity of deposit. Hence no kind of geological structure is of higher importance in the interpretation of the history of the stratified formations of a country. In rare cases an unconformability may occur between two horizontal groups of strata. On the left side of Fig. 311, for instance, the beds *d* follow horizontally upon the horizontal beds (*a*). Were merely a limited section visible disclosing only this relation of the rocks, the two groups *a* and *d* might be mistaken for conformable portions of one continuous series. Further examination, however, would lead to the detection of evidence that the limestone *a* had been upraised and unequally denuded before the deposition of the overlying strata *b c d*. This denudation would show that the apparent conformability was accidental, that the older rock had really been upraised and worn down before the formation of the newer. In such a case the upheaval must have been so uniform over some tracts as not to disturb the horizontality of the lower strata.

As a rule, however, it seldom happens that movements of this kind have taken place over an extensive area so equably as not to produce a want of coincidence somewhere between the older and newer rocks. Most frequently the older formations have been tilted at various angles, or even placed on end. They have likewise been irregularly and often enormously worn down. Hence, instead of lying parallel, the younger beds run transgressively across the upturned denuded ends of the older. The greater the disturbance of the older rocks the more marked is the unconformability. In

[1] The occurrence of considerable contemporaneous erosion between undoubtedly conformable strata belonging to one continuous geological series has already (p. 480) been described.

Fig. 312, the lower series of beds (*c*) has been upturned and denuded before the deposition of the upper series (*a b*) upon them. In this instance the upper worn surface of the limestones *c* has been perforated by boring molluscs below the sandy stratum (*b*).

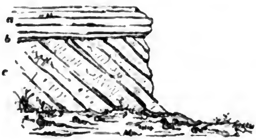


FIG. 312.—UNCONFORMABILITY BETWEEN HORIZONTAL AND INCLINED STRATA. INFERIOR OOLITE (*a b*) RESTING ON CARBONIFEROUS LIMESTONE (*c*), FROME, SOMERSET (*B.*).

An unconformability forms one of the great breaks in the geological record. In Fig. 213 (p. 495), by way of illustration, we see at once that a notable hiatus in deposition, and therefore in geological chronology, must exist between the older conformable series, *a b c*, and the later strata by which these are covered. The former had been deposited, folded, upheaved, and worn down before the accumulation of the newer series upon their denuded edges. These changes must have demanded a considerable lapse of time. Yet, looking merely at the structure in itself, we have evidently no means of fixing, even relatively, the length of interval marked by an unconformability. By ascertaining from some other region the full suite of formations we learn what members of the succession are wanting. In this way it would be discovered that the greater part of the Carboniferous system, the whole of the Permian, and the Trias up to the base of the Lias are absent from the ground represented in Fig. 311. The mere violence of contrast between a set of vertical beds below and a horizontal group above is in itself no certainly reliable criterion of the relative lapse of time between their deposition, for obviously an older portion of a given formation might be tilted on end and be overlaid unconformably by a later part of the same formation. A set of flat rocks of high geological antiquity may, on the other hand, be conformably covered by a formation of comparatively recent date, yet in spite of the want of discordance between the two, they might have been separated by a large portion of the total sum of geological time. Further examination will usually suffice to show that the conformability in such cases is only partial or accidental, and that localities may be found where the formations are distinctly unconformable. From the centre of the section in Fig. 313, for example, the two groups of rocks might on casual examination be pronounced to be conformable. Yet at short distances on either side proofs of violent unconformability are conspicuous. It sometimes happens

FIG. 313.—SECTION OF LOCAL DECEPTIVE CONFORMABILITY.

that more than one unconformability may be detected in the same section. Thus in Fig. 314, the break between the quartzite (*q*) and Old Red Sandstone (*s*) is to the eye much more violent and complete than that between the sandstone and the overlying gravels

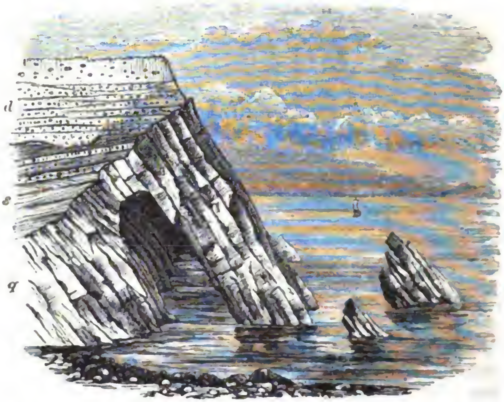


Fig. 314.—Double Unconformability at Cullen, Banffshire.
q, Quartzite; *s*, Old Red Sandstone; *d*, Post-Tertiary Gravels.

and clays (*d*). Yet there can be no doubt that the interval separating the epoch of the quartzite from that of the sandstone was brief when compared with the vast lapse of time that intervened between the nearly flat sandstones and overlying superficial deposits. It is by the evidence of organic remains that the relative importance of unconformabilities must be measured, as will be explained in Book V.

Paramount though the effect of an unconformability may be in the geological structure of a country, it must nevertheless be, when viewed on the large scale, merely local. The disturbance by which it was produced can have affected but a comparatively circumscribed region, beyond the limits of which the continuity of sedimentation may have been undisturbed. We may therefore always expect to be able to fill up the gaps in one district or country from the more complete geological formations of another.

BOOK V.

PALÆONTOLOGICAL GEOLOGY.

PALÆONTOLOGY treats of the structure, affinities, classification, and distribution in time of the forms of plant and animal life imbedded in the rocks of the earth's crust. Considered from the biological side it is a part of zoology and botany. A proper knowledge of extinct organisms can only be attained by the study of living forms, while our acquaintance with the history and structure of modern organisms is amplified by the investigation of their extinct progenitors. Viewed, on the other hand, from the physical side, palæontology is a branch of geology. It is mainly in this latter aspect that it will here be discussed.

Palæontology or Palæontological geology deals with fossils or organic remains preserved in natural deposits, and endeavours to gather from them information as to the history of the globe and its inhabitants. The term fossil, meaning literally anything "dug up," was formerly applied indiscriminately to any mineral substance taken out of the earth's crust, whether organized or not. Ordinary minerals and rocks were thus included as fossils. For many years, however, the meaning of the word has been so restricted as to include only the remains or traces of plants and animals preserved in any natural formation, whether hard rock or loose superficial deposit. The idea of antiquity or relative date is not necessarily involved in this conception of the term. Thus the bones of a sheep buried under gravel and silt by a modern flood, and the obscure crystalline traces of a coral in ancient masses of limestone, are equally fossils. Nor has the term fossil any limitation as to organic grade. It includes not merely the remains of organisms, but also whatever was directly connected with or produced by these organisms. Thus the resin which was exuded from trees of long-perished forests is as much a fossil as any portion of the stem, leaves, flowers, or fruit, and in some respects is even more valuable to the geologist than more determinable remains of its parent trees, because it has often preserved in admirable perfection the insects which flitted about in the woodlands. The burrows and trails of a worm preserved in sandstone and shale claim recognition as fossils, and indeed are commonly the only indications to be met with of the existence of annelide life among old geological formations. The droppings

(coprolites) of fishes and reptiles are excellent fossils, and tell their tale as to the presence and food of vertebrate life in ancient waters. The little agglutinated cases of the caddis-worm remain as fossils in formations from which perchance most other traces of life may have passed away. Nay, the very handiwork of man, when preserved in any natural manner, is entitled to rank among fossils; as where his flint-implements have been dropped into the prehistoric gravels of river-valleys, or where his canoes have been buried in the silt of lake-bottoms.

The term fossil, moreover, suffers no restriction as to the condition or state of preservation of any organism. In some rare instances the very flesh, skin, and hair of a mammal have been preserved for thousands of years, as in the case of the mammoths entombed within the frozen mud cliffs of Siberia. Generally all or most of the original animal matter has disappeared, and the organism has been more or less completely mineralized or petrified. It often happens that the whole organism has decayed, and a mere cast in amorphous mineral matter, as sand, clay, ironstone, silica, or limestone, remains; yet all these variations must be comprised in the comprehensive term fossil.

Two preliminary questions demand attention: in the first place how remains of plants and animals come to be entombed in rocks, and in the second how they have been preserved there so as now to be recognizable.

i. Conditions for the entombment of organic remains.—If what takes place at the present day may fairly be taken as an indication of what has been the ordinary condition of things in the geological past, there must have been so many chances against the conservation of either animal or plant remains that their occurrence among stratified formations should be regarded as exceptional, and as the result of various fortunate accidents.

1. On land.—Let us consider, in the first place, what chances exist for the preservation of remains of the present fauna and flora of a country. The surface of the land may be densely clothed with forest, and abundantly peopled with animal life. But the trees die and moulder into soil. The animals, too, disappear, generation after generation, and leave few perceptible traces of their existence. If we were not aware from authentic records that central and northern Europe was covered with vast forests at the beginning of our era, how could we know this fact? What has become of the herds of wild oxen, the bears, wolves, and other denizens of the lowlands of primeval Europe? How could we prove from the examination of the soil of any European country that those creatures though now extinct had once abounded there? We might search in vain for any such superficial traces, and should learn by so doing that the law of nature is everywhere "dust to dust."

The conditions for the preservation of relics of terrestrial (including freshwater) plant and animal life must therefore be always local,

and, so to say, exceptional. They are supplied only where organic remains can be protected from air and superficial decay. Hence they may be observed in

a. Lakes.—Over the floor of a lake deposits of silt, peat, marl, &c., are formed. Into these the trunks, branches, leaves, flowers, fruits, or seeds of plants from the neighbouring land may be carried, together with the bodies of vertebrates, birds, and insects. An occasional storm may blow the lighter debris of the woodlands into the water. Such portions of the wreck as are not washed ashore again may sink to the bottom, where they will for the most part probably rot away, so that, in the end, only a very small fraction of the whole vegetable matter cast over the lake by the wind is covered up and preserved at the bottom. In like manner the remains of volant and wild animals swept by winds or by river floods into the lake run so many risks of dissolution that only a proportion of them, and probably merely a small proportion, would be preserved. When we consider these chances against the conservation of the vegetable and animal life of the land, we must admit that, at the best, lake-bottoms can contain but a meagre and imperfect representation of the abundant life of the adjacent hills and plains. Lakes, however, have a distinct flora and fauna of their own. Their aquatic plants may be entombed in the gathering deposits of the bottom. Their molluscs, of characteristic types, sometimes form, by the accumulation of their remains, sheets of soft calcareous marl (p. 463) in which many of the undecayed shells are preserved. Their fishes, likewise distinctly lacustrine, no doubt must often be entombed in the silt or marl.

b. Peat-mosses.—Wild animals venturing on the more treacherous watery parts of peat-bogs are sometimes engulfed or "laired." The antiseptic qualities of the peat preserve their remains from decay. Hence from European peat-mosses numerous remains of deer and oxen have been exhumed. Evidently the larger beasts of the forest ought chiefly to be looked for in these localities (p. 460).

c. Deltas at River Mouths.—It is obvious that to some extent both the flora and the fauna of the land may be buried among the sand and silt of deltas (p. 388). But though occasional or frequent river-floods sweep down trees, herbage, and the bodies of land animals, the carcases so transported run every risk of having their bones separated and dispersed, or of decaying or being otherwise destroyed while still afloat, while even if they reach the bottom they tend to dissolution there unless speedily covered up and protected by fresh sediment. Delta formations can scarcely be expected to preserve more than a meagre outline of the varied terrestrial flora and fauna.

d. Caverns.—These are eminently adapted for the preservation of the higher forms of terrestrial life (p. 355). Most of our knowledge of the prehistoric mammalian fauna of Europe is derived from what has been disinterred from *bone-caves.* As these recesses lie for the

most part in limestone or in calcareous rock, their floors are commonly coated with stalagmite from the drip of the roof; and as this deposit is of great closeness and durability it has effectually preserved whatever it has covered or enveloped. The caves have in many instances served as dens wherein predatory beasts, like the hyæna, cave-lion, and cave-bear slept, and into which some of them dragged their prey. In other cases they have been merely holes whither different animals crawled to die, or into which they fell or were swept by inundations. Under whatever circumstances the animals left their remains in these subterranean retreats, the result has been that the bones have been covered up and preserved. Still we must admit that, after all, only a fraction even of the mammals of the time would enter the caves, and, therefore, that the evidence of the cavern-deposits, profoundly interesting and valuable as it is, presents us with merely a glimpse of one aspect of the life of the land.

e. Mineral-springs.—The deposits of mineral matter resulting from the evaporation of mineral springs on the surface of the ground serve as receptacles for occasional leaves, land-shells, insects, dead birds, small mammals, and other remains of the plant and animal life of the land (pp. 354, 461).

f. Volcanic deposits.—Sheets of lava and showers of volcanic dust may entomb terrestrial organisms (pp. 207, 231). It is obvious, however, that even over the areas wherein volcanoes occur and continue active they can only to a very limited extent entomb and preserve the flora and fauna of the land.

2. In the Sea.—In the next place, if we turn to the sea, we find certainly more favourable conditions for the preservation of organic forms, but also many circumstances which operate against it. While the level of the land remains stationary, there can be but little effective entombment of marine organisms in littoral deposits; for only a limited accumulation of sediment will be formed until subsidence of the sea-floor takes place. In the trifling beds of sand or gravel thrown up on a stationary shore, only the harder and more durable forms of life, such as gasteropods and lamellibranchs, which can withstand the triturating effects of the beach waves, are likely to remain uneffaced.

Below tide-marks, along the margin of land whence sediment is derived, conditions are more favourable for the preservation of marine organisms. Sheets of sand and mud are there laid down, wherein the harder parts of many forms of life may be entombed and protected from decay. But only a small proportion of the total marine fauna may be expected to occur in such deposits. At the best, merely littoral and shallow-water forms will occur, and even of these there can be no considerable proportion imbedded and preserved, save where a sufficiently abundant and rapid deposit of sediment is combined with a slow depression of the sea-bottom. But under the most favourable conditions they will hardly represent

more than a mere fraction of the whole assemblage of life in these juxta-terrestrial parts of the ocean. In proportion to distance from land the rate of deposition of sediment on the sea-floor must become feebler, until in the remote central abysses it reaches a hardly appreciable minimum, while at the same time the solution of calcareous organisms by carbonic acid may become marked in deep water. Except, therefore, where organic deposits, such as ooze, are forming in these more pelagic regions, the conditions must be on the whole unfavourable for the preservation of any adequate representation of the deep-sea fauna. Hard enduring objects, such as teeth and bones, may slowly accumulate and be protected by a coating of peroxide of manganese, or of silicates, such as are now forming here and there over the deep sea-bottom. Yet a deposit of this nature, if raised into land, would supply but a meagre picture of the life of the sea.

In considering the various conditions under which marine organisms may be entombed and preserved, we must take into account certain occasional phenomena, when sudden or at least rapid and extensive destruction of the fauna of the sea may be caused. Earthquake shocks have been followed by the washing ashore of vast quantities of dead fish, and no doubt submarine volcanic eruptions must likewise be destructive to the denizens of the sea-bottom. Violent storms, by driving shoals of fishes into shallow water and against rocks, produce enormous destruction. Dr. Leith Adams describes the coast of part of the Bay of Fundy as being covered to a depth of a foot in some places with dead fish dashed ashore by a storm on the 24th of September, 1867.[1] Copious discharges of fresh water into the sea have been observed to cause extensive mortality among marine organisms. Thus, during the S.W. monsoon and accompanying heavy rains, the west coasts of some parts of India are covered with dead fish thrown ashore from the sea.[2] Even a sudden irruption from the outer sea into a sheltered and partially brackish inlet may cause the extinction of many of the denizens of the latter, though a few may be able to survive the altered conditions.[3] Such phenomena offer explanations of the probable causes of death in the case of fossil fishes, whose remains are sometimes crowded together in various geological formations.

Of the whole sea-floor the area best adapted for preserving a varied suite of marine organic exuviæ is obviously that belt which, running along the margin of the land, is ever receiving fresh layers of sediment transported by rivers and currents from the adjacent shores. The most favourable conditions for the accumulation of a thick mass of marine fossiliferous strata will arise when the area of deposit is undergoing a gradual subsidence. If the rate of depression and that of deposit be equal, or nearly so, the movement may proceed for a vast period without producing any great apparent change

[1] *Q. J. Geol. Soc.* xxix. p. 303.
[2] Denison, *Op. cit.* xviii. p. 453.
[3] Forchhammer, *Edin. New. Phil. Journ.* xxxi. p. 69. Large numbers of salmon sometimes die in pools of a river during dry and hot weather.

in marine geography, and even without seriously affecting the distribution of life over the sea-floor within the area of subsidence. Hundreds or thousands of feet of sedimentary strata may conceivably be in this way heaped up round the continents, containing a fragmentary series of remains, chiefly forms of shallow-water life which had hard parts capable of preservation.

There can be little doubt that such has in fact been the history of the main mass of stratified formations in the earth's crust. These piles of marine strata have unquestionably been laid down in comparatively shallow water within the area of deposit of terrestrial sediment. Their great depth seems only explicable by prolonged and repeated movements of subsidence, interrupted, however, as we know, by other movements of a contrary kind. These geographical changes affected at once the deposition of inorganic materials and the succession of organic forms. One series of strata is sometimes abruptly succeeded by another of a very different character, and we generally find a corresponding contrast between their respective organic contents.

It follows from these conclusions that representatives of the abysmal deposits of the central oceans are not likely to be met with among the geological formations of past times. Thanks to the great work done by the *Challenger* expedition, we know what are the leading characters of the accumulations now forming on the deeper parts of the ocean floor. They have absolutely no analogy among the formations of the earth's crust. They differ, indeed, so entirely from any formation which geologists have considered to be of deep-water origin as to indicate that, from early geological times, the present great areas of land and sea have remained on the whole where they are, and that the land consists mainly of strata formed, at successive epochs, of terrestrial debris laid down in the surrounding shallow sea.

ii. Preservation of organic remains in mineral masses.—The condition of the remains of plants and animals in rock-formations depends, first, upon the original structure and composition of the organisms, and secondly, upon the manner in which their fossilization has been effected.

1. Influence of original structure and composition.—The internal skeletons of most vertebrate animals consist mainly of phosphate of lime. In saurians and fishes there is also an exoskeleton of hard bony plates or of scales. It is these durable portions that remain as evidence of the former existence of vertebrate life. The hard parts of invertebrates present a greater variety of composition. In the vast majority of cases they consist of calcareous matter, either calcite or aragonite (pp. 82, 83). The carbonate of lime is occasionally strengthened by phosphate, while in a few cases, as in the horny brachiopods, in *conularia, serpula*, and some other forms, the phosphate is the chief constituent.[1] Next in abundance to lime

[1] Logan and Hunt. *Amer. Journ. Sci.* xvii. (1854), p. 235.

is silica, which constitutes the frustules of diatoms and the harder parts of many protozoa, and is found also in the teeth of some molluscs. The integuments of insects, the carapaces of crustacea, and some other organisms are composed fundamentally of chitin,[1] a transparent horny substance which can long resist decomposition. In the vegetable kingdom the substance known as cellulose forms the essential part of the framework of plants. In dry air it possesses considerable durability, also when thoroughly water-logged and excluded from meteoric influences. In the latter condition, imbedded amid mud or sand, it may last until gradually petrified.

It is a familiar fact that in the same stratum different organisms occur in remarkably different states of fossilization. This is sometimes strikingly exemplified among the mollusca. The conditions for their preservation may have been the same, yet some kinds of shells are found only as empty moulds or casts, while others still retain their form, composition, and structure. This discrepancy, no doubt, points to original differences of chemical composition. The aragonite shells of a stratum may be entirely dissolved, while those of calcite may remain (pp. 82, 166). The presence, therefore, only of calcite forms does not necessarily imply that others of aragonite were not originally present. But the conditions of fossilization have likewise greatly varied. In the clays of the Mesozoic formations, for example, cephalopods may be exhumed retaining even their pearly nacre, while in corresponding deposits among the Palæozoic systems they are merely crystalline calcite casts.

2. Fossilization.—The numerous forms of fossilization may be reduced to three leading types.

(1.) *The original substance is partly or wholly preserved.* Several grades may be noticed: (*a*) where the entire animal substance is retained, as in the frozen carcases of mammoths in the Siberian cliffs; (*b*), where the organism has been mummified by being encased in resin or gum (insects in amber); (*c*), where the organism has been carbonized with or without retention of its structure, as is characteristically shown in peat, lignite, and coal; (*d*) where a variable portion of the original substance, and especially the organic matter, has been removed, as happens with shells and bones: this is no doubt one of the first steps towards petrifaction.

(2.) *The original substance is entirely removed with retention merely of external form.*—Mineral matter gathers round the organism and hardens there while the organism itself decays. Eventually a mere mould of the plant or animal is left in stone. Every stage in this process may be studied along the margin of calcareous springs and streams (*ante*, p. 461). The lime in solution is precipitated round fibres of moss, leaves, twigs, &c., which are thereby incrusted with mineral matter. While the crust thickens the organism inside decays, until a

[1] According to O. Schmidt, the composition of this substance is C, 46·64; H, 6·60; N, 6·66; O, 40·20. The brown chitin of Scottish Carboniferous scorpions is hardly distinguishable from that of recent species.

mere hollow mould of its form remains. Among stratified rocks these moulds are of frequent occurrence. They may be subsequently filled up by mineral matter washed in mechanically or deposited as a chemical precipitate. Such casts are particularly common in sandstone, which, being a porous rock, has allowed water to filter through it and remove the substance of enclosed plant-stems, shells, &c. In the sandstones of the Carboniferous system casts in compacted sand of stems of *lepidodendron* and other plants are abundant. It is obvious that in casts of this kind no trace remains of the original structure of the organism, save merely of its external form.

(3.) *The original substance is molecularly replaced by mineral matter with partial or entire preservation of internal structure.*—This is the only true petrifaction. The process consists in the abstraction of the organic substances, molecule by molecule, and in their replacement by precipitated mineral matter. So gradual and thorough has this interchange often been, that the minutest structures of plant and animal have been perfectly preserved. Silicified wood is a familiar example.

The chief substance which has replaced organic forms in rock formations is calcite, either crystalline or in an amorphous granular condition. In assuming a crystalline (or fibrous) form this mineral has often observed a symmetrical grouping of its component individuals, these being usually placed with their long axes perpendicular to the surface of an organism. In many cases among invertebrate remains the calcite now visible is pseudomorphous after aragonite (p. 166). Next in abundance as a petrifying medium is silica, most commonly in the colloid form (calcedony, opal), but also as quartz. It is specially frequent in some limestones, as chert and flint, replacing the carbonate of lime in molluscs, echinoderms, corals, &c. It also occurs in irregular aggregates in which organisms are sometimes beautifully preserved. It forms a frequent material for the petrifaction of fossil wood. Silicification, or the replacement of organisms by silica, is the process by which minute organic structures have been most perfectly preserved. In a microscopic section of silicified wood, the organization of the original plant may be as distinct as in the section of any modern tree. Pyrites and marcasite are common replacing minerals, especially in argillaceous deposits, as, for example, among the clays of Jurassic and Cretaceous formations. Siderite has played a similar part among the ironstones of the coal-measures, where shells (*Anthracosia*, &c.) and plants have been replaced by it. Many other minerals are occasionally found to have been substituted for the original substance of organic remains. Among these may be mentioned glauconite (replacing or filling foraminifera), vivianite (specially frequent as a coating on the weathered surface of scales and bones), barytes, celestine, gypsum, talc, lead-sulphate, carbonate, and sulphide, copper-sulphide and native copper, hæmatite and limonite, zinc-carbonate and sulphide, cinnabar, sulphur, fluorite, phosphorite.[1]

iii. Relative Palæontological Value of Organic Remains.—As the conditions for the preservation of organic remains exist more

[1] Roth, *Chem. Geol.* i. p. 605.

favourably under the sea than on land, marine must be far more abundantly conserved than terrestrial organisms. This is true to-day, and has doubtless been true in all past geological time. Hence for the purposes of the geologist, fossil remains of marine forms of life far surpass all others in value. Among them there will necessarily be gradation in importance, regulated chiefly by their possession of hard parts readily susceptible of preservation among marine deposits. Among the Protozoa, foraminifers, radiolarians, and sponges, possessing siliceous or calcareous organizations, have been preserved in deposits of all ages. Of the Cœlenterates those which, like the corals, secrete a calcareous skeleton are important rock-builders. The Echinoderms have been so abundantly preserved that their geological history and development are better known than those of most other classes of invertebrates. The Annelides, on the other hand (except where they have been tubicolar), have almost entirely disappeared, though their former presence is often revealed by the trails they have left upon surfaces of sand and mud. Of all the marine tribes which live within the juxta-terrestrial belt of sedimentation, unquestionably the Mollusca stand in the front rank as regards their aptitude for becoming fossils. In the first place, they almost all possess a hard durable shell, composed chiefly of mineral matter, capable of resisting considerable abrasion, and readily passing into a mineralized condition. In the next place, they are extremely abundant both as to individuals and genera. They occur on the shore up to high-water mark, and range thence down into the abysses. Moreover, they appear to have possessed these qualifications from early geological times. In the marine Mollusca, therefore, we have a common ground of comparison between the stratified formations of different periods. They have been styled the alphabet of palæontological inquiry. It will be seen, as we proceed, how much, in the interpretation of geological history, depends upon the testimony of sea-shells.

Turning next to the organisms of the land, we perceive that the abundant terrestrial flora has a comparatively small chance of being well represented in a fossil state; that indeed, as a rule, only that portion of it of which the leaves, twigs, flowers, fruits, or trunks are blown into lakes, or swept down by rivers, is likely to be partially preserved. Terrestrial plants, therefore, occur in comparative rarity among stratified rocks, and furnish in consequence only limited means of comparison between the formations of different ages and countries. Of land animals the vast majority perish, and leave no permanent trace of their existence. Predatory and other forms whose remains may be looked for in caverns or peat-mosses, must occur more numerously in the fossil state than birds, and are correspondingly more valuable to the geologist for the comparison of different strata.

Another character determines the relative importance of fossils as geological monuments. All organisms have not the same inherent capability of persistence. The longevity of an organic type has, on

the whole, been in inverse proportion to its perfection. The more complex its structure, the more susceptible has it been of change, and consequently the less likely to be able to withstand the influences of changing climate, and other physical conditions. A living species of foraminifer or brachiopod, endowed with comparative indifference to its environment, may spread over a vast area of the sea-floor, and the same want of sensibility enables it to endure through the changing physical conditions of successive geological periods. It may thus possess a great range, both in space and time. But a highly-specialized mammal is usually confined to but a limited extent of country, and to a narrow chronological range.

iv. Uses of Fossils in Geology.—Apart from their profound interest as records of the progress of organized being upon the earth, fossils serve two main purposes in geological research: (1) to throw light upon former conditions of physical geography, such as the presence of land, rivers, lakes, and seas, in places where they do not now exist, changes of climate, and the former distribution of plants and animals; and (2) to furnish a guide in geological chronology whereby rocks may be classified according to relative date, and the facts of geological history may be arranged and interpreted as a connected record of the earth's progress.

1. Changes in Physical Geography.—A few examples will suffice to show the manifold assistance which fossils furnish to the geologist in the elucidation of ancient geography.

(*a.*) Former land-surfaces are revealed by the presence of tree-stumps in their positions of growth, with their roots branching freely in the underlying stratum, which, representing the ancient soil, often contains leaves, fruits, and other sylvan remains, together with traces of the bones of land animals, remains of insects, land-shells, &c. Ancient woodland surfaces of this kind, found between tide-marks, and even below low-water line, round different parts of the British coast, unequivocally prove a subsidence of the land (p. 281). Of more ancient date are the "dirt-beds" of Portland, which, by their layers of soil and tree-stumps, show that woodlands of cycads sprang up over an upraised sea-bottom and were buried beneath the silt of a river or lake. Still further back in geological history come the numerous coal-growths of the Carboniferous period, pointing to wide jungles of terrestrial or aquatic plants, like the modern mangrove swamps, which were submerged and covered with sand or silt.

(*b.*) The former existence of lakes can be satisfactorily proved from beds of marl or lacustrine limestone full of freshwater shells, or from fine silt with leaves, fruits, and insect remains. Such deposits are forming abundantly at the present day, and they occur at various horizons among the geological formations of past times. The well-known nagelflue of Switzerland—a mass of conglomerate attaining a thickness of fully 6000 feet—can be shown from its fossil contents to be essentially a lacustrine formation. Still more important are the ancient Eocene and Miocene lake-formations of

North America, whence so rich a terrestrial and lacustrine flora and fauna have been obtained.

(*c.*) Old sea-bottoms are vividly brought before us by beds of marine shells and other organisms. Layers of water-worn gravel and sand, with rolled shells of littoral and infra-littoral species, unmistakeably mark the position of a former shore line. Deeper water is indicated by finer muddy sediment, with relics of the fauna that prevails beneath the reach of waves and ground-swell. Limestones full of corals, or made up of crinoids, point to the slow, continuous growth and decay of generation after generation of organisms in clear sea-water.

(*d.*) Variations in the nature of the water or of the sea-bottom may sometimes be shown by changes in the size or shape of the organic remains. If, for example, the fossils in the central and lower parts of a limestone are large and well-formed, but in the upper layers become dwarfed and distorted, we may reasonably infer that the conditions for their continued existence at the locality must have been gradually impaired. The final complete cessation of these favourable conditions is shown by the replacement of limestone by shale, indicative of the water having become muddy, and by the disappearance of the organisms, which had shown their sensitiveness to the change.

(*e.*) The proximity of land at the time when a fossiliferous stratum was in the course of accumulation is sufficiently proved by mere lithological characters, as has been already explained; but the conclusion may be further strengthened by the occurrence of leaves, stems, and other fragments of terrestrial vegetation which, if found in some numbers among marine organisms, would make it improbable that they had been drifted far from land (see, however, p. 439).

(*f.*) The existence of different conditions of climate in former geological periods is satisfactorily demonstrated from the testimony of fossils. Thus an assemblage of the remains of palms, gourds, and melons, with bones of crocodiles, turtles, and sea-snakes, proves a sub-tropical climate to have prevailed over the south of England in the time of the older Tertiary formations. On the other hand, the extension of an intensely cold or arctic climate far south into Europe during post-Tertiary time can be shown from the existence of the remains of arctic animals even in the south of England and of France. This is a use of fossils, however, where great caution must be used. We cannot affirm that, because a certain species of a genus lives now in a warm part of the globe, every species of that genus must always have lived in similar circumstances. The well-known example of the mammoth and woolly rhinoceros having lived in the cold north, while their modern representatives inhabit some of the warmest regions of the globe, may be usefully remembered as a warning against any such conclusions. When, however, not one fossil merely, but the whole assemblage of fossils in a formation finds its modern analogy in a certain general condition of climate, we

may at least tentatively infer that the same kind of climate prevailed where that assemblage lived. Such an inference would become more and more unsafe in proportion to the antiquity of the fossils and their divergence from existing forms.

2. Geological chronology.—Although absolute dates cannot be fixed in geological chronology, it is not difficult to determine the relative age of different strata. For this purpose the fundamental law is based on the "order of superposition" (p. 500). The law may thus be defined: in a series of stratified formations the older must underlie the younger. It is not needful that we should actually see the one lying below the other. If a continuous conformable succession of strata dips steadily in one direction we know that the beds at the one end must underlie those at the other, because we can trace the whole succession of beds between them. Rare instances occur where strata have been so folded by great terrestrial disturbance that the younger are made to underlie the older. But this inversion can usually be made quite clear from other evidence. The true order of superposition is decisive of the relative ages of stratified rocks.

The order of sequence having been determined, it is needful to find some means of identifying a particular formation elsewhere, where its stratigraphical relations may possibly not be visible. At first it might be thought that the mere external aspect and mineral characters of the rocks ought to be sufficient for this purpose. Undoubtedly these features may suffice within the same limited region in which the order of sequence has already been determined. But as we recede from that region they become more and more unreliable. That this must be the case will readily appear, if we reflect upon the conditions under which sedimentary accumulations have been formed. The markedly lenticular nature of these deposits has already been described (p. 491). At the present day the sea-bottom presents here a bank of gravel, there a sheet of sand, elsewhere layers of mud, or of shells, or of organic ooze, all of which are in course of deposit simultaneously, and will as a rule be found to shade off laterally into each other. The same diversity of contemporaneous deposits has obtained from the earliest geological periods. Conglomerates, sandstones, shales, and limestones occur on all geological horizons, and replace each other even on the same platform. The Coal-measures of Pennsylvania are represented west of the Rocky Mountains by thousands of feet of massive marine limestones. The white chalk of England lies on the same geological horizon with marls and clays in North Germany, thick sandstones in Saxony, hard limestone in the south of France. Mere mineral characters are thus quite unreliable save within comparatively restricted areas.

The solution of this problem was found and was worked out for the Secondary rocks of England by William Smith at the end of last century. It is supplied by organic remains, and depends upon the law that the order of succession of plants and animals has been similar all over the world. According to the order of superposition

the fossils found in a formation must be older than those in the formation above, and younger than those in that below. This order, however, must be first accurately determined; for so far as regards organic structure or affinities, there may be no discoverable reason why a particular species should precede or follow another. Unless, for example, we knew from observation or testimony that *Rhynchonella pleurodon* is a shell of the Carboniferous Limestone, and *Rhynchonella tetrahedra* is a shell of the Lias, we could not, from mere inspection of the fossils themselves, pronounce as to their real geological position. It is quite true that by practice a palæontologist has his eye so trained that he can make shrewd approximations to the actual horizon of fossils which he may never have seen before (and this is more especially true in regard to the mammalia, as will be immediately adverted to), but he can only do this by availing himself of a wide experience based upon the ascertained order of appearance of fossils as determined by the law of superposition. For geological purposes, therefore, and indeed for all purposes of comparison between the faunas and floras of different periods, it is absolutely essential first of all to have the order of superposition of strata rigorously determined. Unless this is done the most fatal mistakes may be made in palæontological chronology. But when it has once been done in one typical district, the order thus established may be held as proved for a wide region where, from paucity of sections, or from geological disturbance, the true succession of formations cannot be satisfactorily determined.

The order of superposition having been determined in a great series of stratified formations, it is found that the fossils at the bottom are not quite the same as those at the top of the series. As we trace the beds upward we discover that species after species of the lowest platforms disappears, until perhaps not one of them is found. With the cessation of these older species others make their entrance. These in turn are found to die out and be replaced by newer forms. After patient examination of the rocks, it is ascertained that every well-marked formation is characterized by its own species or genera (type-fossils, Leitfossilien) or by a general assemblage or *facies* of organic forms. This can only, of course, be determined by actual practical experience over an area of some size. The characteristic fossils are not always the most numerous; they are those which occur most constantly and have not been observed to extend their range above or below a definite geological horizon or platform. As illustrations of the type-fossils characteristic of some of the larger subdivisions of the Geological Record, the following may be given. Lepidodendra and Sigillaria are typical of Old Red Sandstone and Carboniferous formations; Graptolites of the Silurian system; Trilobites of Palæozoic rocks from Cambrian to Carboniferous, but most especially of Silurian formations; Cystideans of the older Palæozoic formations; Orthoceratites of Palæozoic and Ammonites of Mesozoic formations; Ichthyosaurs and Plesiosaurs of Mesozoic formations; Nummulites,

Palæotherium, Anoplotherium, Hyopotamus, and Anthracotherium of the older Tertiary formations; Mastodon, Elephant, Hyæna, Cervus, and Equus of younger Tertiary formations. The occurrence of such organisms in any rock at once decides the great division of geological time to which the rock must be assigned.

The type fossils of a formation, after sufficiently prolonged and extended experience, having been ascertained, serve to identify that formation in its progress across a country. Thus, as we trace the formation into tracts where it would be impossible to determine the true order of superposition, owing to the want of sections, or to the disturbed condition of the rocks, we can employ the type-fossils as a means of identification, and speak with confidence as to the succession of the rocks. We may even demonstrate that in some mountainous ground the beds have been turned completely upside down, if we can show that the fossils in what are now the uppermost strata ought properly to lie underneath those in the beds below them.

Prolonged study of the succession of organic types in the geological past all over the world, has given palæontologists some confidence in fixing the relative age even of fossils belonging to previously unknown species or genera, and occurring under circumstances where no order of superposition can be found. For instance, the general sequence of mammalian types having been fixed by the law of superposition, the horizon of a mammaliferous deposit may be approximately determined by the grade or degree of evolution denoted by its mammalian fossils. Thus, should remains be generically abundant, differing from those now living and presenting none of the extreme contrasts which are now found among our higher animals, should they embrace neither true ruminants, nor solipedes, nor proboscidians, nor apes, they might with high probability be referred to the Eocene period.[1] Reasoning of this kind must be based, however, upon a wide basis of evidence, seeing that the progress of development has been far from equal in all ranks of the animal world.

Observations made over a large part of the surface of the globe have enabled geologists to divide the stratified part of the earth's crust into systems, formations, and groups or series. These subdivisions are frequently marked off from each other by lithological characters. But, as already remarked, mere lithological differences afford at the best but a limited and local ground of separation. Two masses of sandstone, for example, having exactly the same general external and internal characters, may belong to very different geological periods. On the other hand, a series of limestones in one locality may be the exact chronological equivalent of a set of sandstones and conglomerates at another, and of a series of shales and clays at a third.

Some clue is accordingly needed which will permit the divisions of the stratified rocks to be grouped and compared chronologically. This fortunately is well supplied by their characteristic fossils.

[1] Gaudry, "Les enchainements du Monde Animal," 1878, p. 246.

Each formation being distinguished by its own assemblage of organic remains, it can be followed and recognized even amid the crumplings and dislocations of a disturbed region. The same general succession of organic types has been observed over a large part of the world, though, of course, with important modifications in different countries. This similarity of succession has been termed *homotaxis*—a term which expresses the fact that the order in which the leading types of organized existence have appeared upon the earth has been similar even in widely separated regions.[1]

It is evident that in this way a method of comparison is furnished whereby the stratified formations of different parts of the earth's crust can be brought into relation with each other. We find, for example, that a certain series of strata is characterized in Britain by certain genera and species of corals, brachiopods, lamellibranchs, gasteropods, and cephalopods. A group of rocks in Bohemia, differing more or less from these in lithological aspect, contains on the whole the same genera, and some even of the same species. In Scandinavia a set of beds may be seen unlike, perhaps, in external characters to the British type, but yielding many of the same fosssils, In Canada and parts of the northern United States, other rocks enclose some of the same, and of closely allied genera and species. All these groups of strata, having the same general facies of organic remains, are classed together as *homotaxial* that is, as having been deposited during the same relative period in the general progress of life in each region.

It was at one time believed, and the belief is still far from extinct, that groups of strata characterized by this community or resemblance of organic remains were chronologically contemporaneous. But such an inference rests upon most insecure grounds. We may not be able to disprove the assertion that the strata were strictly coeval, but we have only to reflect on the present conditions of zoological and botanical distribution, and of modern sedimentation, to be assured that the assertion of contemporaneity is a mere assumption. Consider for a moment what would happen were the present surface of any portion of central or southern Europe to be submerged beneath the sea, covered by marine deposits, and then re-elevated into land. The river-terraces and lacustrine marls formed before the time of Julius Cæsar could not be distinguished by any fossil tests from those laid down in the days of Victoria, unless, indeed, traces of human implements were obtainable whereby the progress of civilization during 2000 years might be indicated. So far as regards the shells, bones, and plants preserved in the various formations, it would be absolutely impossible to discriminate their relative dates; they would be classed as "geologically contemporaneous," that is, as having been formed during the same period in the history of life in the European area; yet there might be a difference of 2000 years or more between many of them. Strict contemporaneity

[1] Huxley, *Q. J. Geol. Soc.* xviii. 1862, p. xlvi.

cannot be asserted of any strata merely on the ground of similarity or identity in fossils.

But the phrase "geologically contemporaneous" is too vague to have any chronological value except in a relative sense. To speak of two formations as "contemporaneous" which may have been separated by thousands of years seems rather a misuse of language, though the phraseology has now gained such a footing in geological literature as probably to be inexpugnable. If we turn again for suggestions to the existing distribution of life on the earth (though it is probable that formerly, and particularly among the earlier geological periods, there was considerably greater uniformity in zoological distribution than there is now) we learn that similarity or identity of species and genera holds good on the whole only for limited areas, and consequently, if applied to wide geographical regions, ought to be an argument for diversity rather than for similarity of age. If we suppose the British seas to be raised into dry land, so that the organic relics preserved in their sands and silts could be exhumed and examined, a general or common facies or type would be found, though some species would be more abundant in or entirely confined to the north, while others would show a greater development in the opposite quarter. Still there would be such a similarity throughout the whole that no naturalist would hesitate to regard the organisms as those of one biological province, and belonging to the same great geological period. The region is so small, and its conditions of life so uniform and uninterrupted, that no marked distinction can be drawn between the forms of life in its different parts.

Widening the area of observation, we perceive that as we recede from any given point on the earth's surface the existing forms of life gradually change. Vegetation alters its aspect from climate to climate, and with it come corresponding transformations in the characters of insects, birds, and wild animals. A lake bottom would preserve one suite of organisms in England, but a very different group at the foot of the Himalaya Mountains, yet the deposits at the two places might be absolutely coeval, even as to months and days. If, therefore, in the geological past there has been, as there is now, a grading of plants and animals in great biological provinces, marked off by differences of contour, climate, and geological history, we must conclude that, while strict contemporaneity cannot be predicated of deposits containing the same organic remains, it may actually be true of deposits in which they are quite distinct.[1]

If, then, at the present time, community of organic forms, except in the case of a few almost world-wide species, obtains only in restricted districts, regions, or provinces, it may have been more or

[1] The present geographical distribution of plants and animals has a profound geological interest, but cannot be properly discussed in this volume. The student will find it luminously treated in Darwin's "Origin of Species," chapters xii. and xiii.; Lyell's "Principles of Geology," chapters xxxviii.-xli.; and in Wallace's "Geographical Distribution of Animals," 2 vols. 1876, and his "Island Life," 1880.

less limited also in past time. Similarity or identity of fossils among formations geographically far apart, instead of proving contemporaneity, may be compatible with great discrepancies in the relative epochs of deposit. For on any theory of the origin of species, the spread of a species, still more of any group of species, to a vast distance from the original centre of dispersion, must in most cases have been inconceivably slow. It doubtless occupied so prolonged a time as to allow of almost indefinite changes in physical geography. A species may have disappeared from its primeval birthplace while it continued to flourish in one or more directions in its outward circle of advance. The date of the first appearance and final extinction of that species would thus differ widely according to the locality at which we might examine its remains.

The grand march of life, in its progress from lower to higher forms, has unquestionably been broadly alike in all quarters of the globe. But nothing seems more certain than that its rate of advance has not everywhere been the same. It has moved unequally over the same region. A certain stage of progress may have been reached in one quarter of the globe thousands of years before it was reached in another; though the same general succession of organic types might be found in each region. At the present day, for example, the higher fauna of Australia is more nearly akin to that which flourished in Europe far back in Mesozoic time than to the living fauna of any other region of the globe. There seems also to be now sufficient evidence to warrant the assertion that the progress of terrestrial vegetation has at some geological periods and in some regions, been in advance of that of the marine fauna (see p. 626).

In fine, in every country where the fossiliferous geological formations are well displayed and have been properly examined, the same general order of organic succession can be made out among them. Their relative age within a limited geographical area can be demonstrated by the law of superposition. When, however, the formations of distant countries are compared, all that we can safely affirm regarding them is that those containing the same or a representative assemblage of organic remains belong to the same epoch in the history of biological progress in each area. They are *homotaxial;* but we cannot assert that they are contemporaneous unless we are prepared to include within that term a vague period of many thousands of years.

3. Imperfection of the Geological Record.—Since the fact was insisted upon by Darwin, geologists have more fully recognized that the history of life has been very imperfectly preserved in the stratified parts of the earth's crust. Apart from the fact that, even under the most favourable conditions, only a small proportion of the total flora and fauna of any period could be preserved in the fossil state, enormous gaps occur where from non-deposit of strata no record has been preserved at all. It is as if whole chapters and books were missing from an historical work.

But even where the record may originally have been tolerably full, powerful dislocations have often thrown considerable portions of it out of sight. Sometimes extensive metamorphism has so affected the rocks that their original characters, including their organic contents, have been destroyed. Oftenest of all, denudation has come into play, and vast masses of strata have been entirely worn away, as is shown not only by the erosion of existing land-surfaces but by the abundant unconformabilities in the structure of the earth's crust.

While the mere fact that one series of rocks lies unconformably on another proves the lapse of a considerable interval between their respective dates, the relative length of this interval may sometimes be demonstrated by means of fossil evidence, and by this alone. Let us suppose, for example, that a certain group of formations has been disturbed, upraised, denuded, and covered unconformably by a second group. In lithological characters the two may closely resemble each other, and there may be nothing to show that the gap represented by their unconformability is not of a trifling character. In many cases, indeed, it would be quite impossible to pronounce any well-grounded judgment as to the amount of interval, even measured by the vague relative standards of geological chronology. But if each group contains a well-preserved suite of organic remains, it may not only be possible, but easy, to say how much of the known geological record has been left out between the two sets of formations. By comparing the fossils with those obtained from regions where the geological record is more complete, it may be ascertained perhaps that the lower rocks belong to a certain platform or stage in geological history which for our present purpose we may call D, and that the upper rocks can in like manner be paralleled with stage H. It would be then apparent that at this locality the chronicles of three great geological periods E, F, and G were wanting, which are elsewhere found to be intercalated between D and H. The lapse of time represented by this unconformability would thus be equivalent to that required for the accumulation of the three missing formations in those regions where sedimentation went on undisturbed, or where the record of them has been preserved.

But fossil evidence may be made to prove the existence of gaps which are not otherwise apparent. As has been already remarked, changes in organic forms must, on the whole, have been extremely slow in the geological past. The whole species of a sea-floor could not pass entirely away, and be replaced by other forms, without the lapse of long periods of time. If then among the conformable stratified formations of former ages we encounter abrupt and important changes in the facies of the fossils, we may be certain that these must mark omissions in the record, which we may hope to fill in from a more perfect series elsewhere. The striking palæontological contrasts between unconformable strata are sufficiently explicable. It is not so easy to give a satisfactory account of those which occur where the beds are strictly conformable, and where no evidence can

be observed of any considerable change of physical conditions at the time of deposit. A group of quite conformable strata, having the same general lithological characters throughout, may be marked by a great discrepance between the fossils above and below a certain line. A few species may pass from the one into the other, or perhaps every species may be different. In cases of this kind, when proved to be not merely local but persistent over wide areas, we must admit, notwithstanding the apparently undisturbed and continuous character of the original deposition of the strata, that the abrupt transition from the one facies of fossils to the other must represent a long interval of time which has not been recorded by the deposit of strata. Professor Ramsay, who called attention to these gaps, termed them "breaks in the succession of organic remains."[1] They occur abundantly among the Palæozoic and Secondary rocks which by means of them can be separated into zones and formations. It is obvious, of course, that even though traceable over wide regions, they were not general over the whole globe. There have never been any universal interruptions in the continuity of the chain of being, so far as geological evidence can show. The breaks or apparent interruptions existed only in the sedimentary record, and were produced by geographical changes of various kinds, such as cessation of deposit from failure of sediment owing to seasonal or other changes; alteration in the nature of the sediment or character of the water; variations of climate from whatever cause; more rapid subsidence bringing successive submarine zones into less favourable conditions of temperature, &c.; and volcanic discharges. The physical revolutions, which brought about the breaks were no doubt sometimes general over a whole zoological province, more frequently over a minor region. Thus at the close of the Triassic period the inland basins of central, southern, and western Europe were effaced, and another and different geographical phase was introduced which permitted the spread of the peculiar fauna of the "Avicula contorta zone" from the south of Sweden to the plains of Lombardy, and from the north of Ireland to the eastern end of the Alps. This phase in turn disappeared, to make way for the Lias with its numerous "zones," each distinguished by the maximum development of one or more species of ammonite. These successive geographical revolutions must in many cases have caused the complete extinction of genera and species possessing a small geographical range.

From all these facts it is clear that the geological record, as it now exists, is at the best but an imperfect chronicle of geological history. In no country is it complete. The lacunæ of one region may be supplied from another; yet in proportion to the geographical distance between the localities where the gaps occur and those whence the missing intervals are supplied, the element of uncertainty in our reading of the record is increased. The most desirable method of research is to exhaust the evidence for each area or province, and to

[1] *Q. J. Geol. Soc.* xix. p. 36.

compare the general order of its succession as a whole with that which can be established for other provinces. It is, therefore, only after long and patient observation and comparison that the geological history of different quarters of the globe can be correlated.

4. Subdivisions of the Geological Record by means of fossils.—As fossil evidence furnishes a much more satisfactory and widely applicable means of subdividing the stratified rocks of the earth's crust than mere lithological characters, it is made the basis of the geological classification of these rocks. Thus a particular stratum may be ascertained to be marked by the occurrence in it of various fossils, one or more of which may be distinctive, either from occurring in no other bed above and below, or from special abundance in that stratum. These species may therefore be used as a guide to the occurrence of the bed in question, which may be called by the name of the most abundant species. In this way a geological horizon or zone is marked off, and geologists thereafter recognize its exact position in the series of formations. But before such a generalization can be safely made, we must be sure that the species in question really never does characterize any other platform. This evidently demands wide experience over an extended field of observation. The assertion that a particular species or genus occurs only on one horizon, or within certain limits, manifestly rests on negative evidence as much as on positive. The palæontologist who makes it cannot mean more than that he knows the species or genus to lie on that horizon or within those limits, and that, so far as his own experience and that of others goes, it has never been met with anywhere else. But a single instance of the occurrence of the fossil on a different zone would greatly damage the value of his generalization, and a few such cases would demolish it altogether. The genus *Arethusina*, for example, had long been known as a characteristic trilobite of the lower zones of the third or highest fauna of the Bohemian Silurian basin. So abundant is one species (*A. Konincki*) that Barrande mentions that he had collected more than 6000 specimens of it, generally in good preservation. But no trace of it had ever been met with towards the upper limit of the Silurian fauna. Eventually, however, a single specimen of a species so nearly identical as to be readily pronounced the same was disinterred from the upper Devonian rocks of Westphalia—a horizon separated from the upper limit of the genus in Bohemia by at least half of the vertical height of the Upper Silurian and by the whole of the lower and middle Devonian formations.[1] Such an example teaches the danger of founding too much on negative data. To establish a geological horizon on limited fossil evidence, and then to assume the identity of all strata containing the same fossils, is to reason in a circle and to introduce utter confusion into our interpretation of the geological record. The first and fundamental point is to determine accurately the order of superposition of the strata.

[1] Barrande, "Réapparition du genre Arethusina," Prague, 1868.

Until this is done detailed palæontological classification may prove to be worthless.

From what has been above advanced it must be evident that, even if the several groups in a formation or system of rocks in any district or country have been found susceptible of minute subdivision by means of their characteristic fossils, and if, after the lapse of many years, no discovery has occurred to alter the established order of succession of these fossils, nevertheless the subdivisions may only hold good for the region in which they have been made. They must not be assumed to be strictly applicable everywhere. Advancing into another district or country where the petrographical characters of the same formation or system indicate that the original conditions of deposit must have been very different, we ought to be prepared to find a greater or less departure from the first observed, or what we unconsciously and not unnaturally come to look upon as the normal order of organic succession. There can be no doubt that the appearance of new organic forms in any locality has been in large measure connected with such physical changes as are indicated by diversities of sedimentary materials and arrangement. The Upper Silurian formations, for example, as studied by Murchison in Shropshire and the adjacent counties, present a clear sequence of strata well defined by characteristic fossils. But within a distance of sixty miles it becomes impossible to establish these subdivisions by fossil evidence. If we examine corresponding strata in Scotland, we find that they contain some fossils which never rise above the Lower Silurian formations in Wales and the west of England. Again, in Bohemia and in Russia we meet with still greater departures from the order of appearance in the original Silurian area, some of the most characteristic Upper Silurian organisms being there found far down beneath strata replete with records of Lower Silurian life. Nevertheless the general succession of life from Lower to Upper Silurian types remains distinctly traceable. Such facts warn us against the danger of being led astray by an artificial precision of palæontological detail. Even where the palæontological sequence is best established, it rests probably in most cases not merely upon the actual chronological succession of organic forms, but also, far more than is usually imagined, upon original accidental differences of local physical conditions. As these conditions have constantly varied from region to region, it must comparatively seldom happen that the same minute palæontological subdivisions, so important and instructive in themselves, can be identified and paralleled, except over comparatively limited geographical areas. The remarkable "zones" of the Lias have been recognized over central and western Europe, but cease to be traceable as we recede from their original geographical province.

v. Bearing of palæontological data upon Evolution.—Since the researches of William Smith at the end of last century it has

been well understood that the stratified portion of the earth's crust contains a suite of organic remains in which a gradual progression can be traced from simple forms of invertebrate life among the early formations to the most highly differentiated mammalia of the present time. Until the appearance of Darwin's "Origin of Species" in 1859 the significance of this progression and its connection with the biological relations of existing faunas and floras were only dimly perceived. Darwin, however, urged that, instead of being fixed or but slightly alterable forms, species might be derived from others, and that processes were at work whereby it was conceivable that the whole of the existing animal and vegetable worlds might have descended from at most a very few original forms. From a large array of facts drawn from observations made upon domestic plants and animals he inferred that from time to time slight peculiarities due to differences of climate, &c., appear in the offspring which were not present in the parent, that these peculiarities may be transmitted to succeeding generations, especially where from their nature they are useful in enabling their possessors to maintain themselves in the general struggle for life. Hence varieties at first arising from accidental circumstances may become permanent, while the original form from which they sprang, being less well adapted to hold its own, perishes. Varieties become species and specific differences pass in the same way into generic. The most successful forms are by a process of "natural selection" made to overcome and survive those that are less fortunate. Hence the "survival of the fittest" is conceived to be the general law of nature. The present varied life of the globe may thus be explained by the continued accumulation, perpetuation, and increase of differences in the evolution, of plants and animals during the whole of geological time. Hence the geological record should contain a more or less full chronicle of the progress of this long history of development.

It is now well known that in the embryonic development of animals there are traces of a progress from lower or more generalized to higher or more specialized types. Since Mr. Darwin's great work appeared, naturalists have devoted a vast amount of research to the subject, and have sought with persevering enthusiasm for any indications of a relation between the order of appearance of organic forms in time and in embryonic development, and for evidence that species and genera of plants and animals have come into existence in the order which, according to the theory of evolution, might have been anticipated.

It must be conceded that on the whole the testimony of the rocks is in favour of the doctrine of evolution. That there are difficulties still unexplained must be frankly granted. Mr. Darwin strongly insisted, and with obvious justice, on the imperfection of the geological record as one great source of these difficulties. Objections to the development theory may, as shown by Mr. Carruthers, be drawn from the observed

order of succession of plants, and the absence of transitional forms among them. Ferns, equisetums, and lycopods appear as far back as the Old Red Sandstone, not in simple or more generalized, but in more complex structures than their living representatives. The earliest known conifers were well-developed trees with woody structure and fruits as highly differentiated as those of their living representatives. The oldest dicotyledons yet found, those of the upper Cretaceous formations, contain representatives of the three great divisions of *Apetalæ*, *Monopetalæ*, and *Polypetalæ*, in the same deposit. These "are not generalized types, but differentiated forms which, during the intervening epochs, have not developed even into higher generic groups."[1]

Professor A. Agassiz has recently drawn attention to the parallelism between embryonic development and palæontological history. Taking the sea-urchins as an illustrative group, he points out the interesting analogies between the immature conditions of living forms and the appearance of corresponding phases in fossil genera. He admits, however, that no early type has yet been discovered whence star-fishes, sea-urchins, or ophiurans might have sprung; that the several orders of echinoderms appear at the same time in the geological record, and that it is impossible to trace anything like a sequence of genera or direct filiation in the palæontological succession of the echinids, though he does not at all dispute the validity of the theory which regards the present echinids as having come down in direct succession from those of older geological times.[2] In the case of the numerous genera which have continued to exist without interruption from early geological periods and have been termed "persistent types," it is impossible not to admit that the existing forms are the direct descendants of those of former ages. If, then, some genera have unquestionably been continuous, the evolutionist argues, it may reasonably be inferred that continuity has been the law, and that even where the successive steps of the change cannot be traced, every genus of the living world is genetically related to other genera now extinct.

Among the fossil mammalia many indications have been pointed out of an evolution of structure. Of these, one of the best known and most striking is the genealogy of the horse, as worked out by Professor O. C. Marsh.[3] The original, and as yet undiscovered, ancestor of our modern horse had five toes on each foot. In the oldest known equine type (Eohippus—an animal about the size of a fox, belonging to the early part of the Eocene period) there were four well-developed toes, with the rudiment of a fifth, on each fore-foot, and three on each hind foot. In a later part of the same geological period appeared the Orohippus, a creature of about the same size, but with only four toes in front and three behind. Traced upwards into younger divisions of the Tertiary series, the size of the animal increases, but the number of digits diminishes, until we reach the modern *Equus*, with its single toe and rudimentary splint-bones.

Another remarkable example, that of the camels, is cited by Professor E. D. Cope. The succession of genera is seen in the same

[1] Carruthers, *Geol. Mag.* 1876, p. 362.
[2] *Ann. Mag. Nat. Hist.* Nov. 1880, p. 369. "Report on Echinoidea," *Challenger Expedition*, vol. iii. p. 19.
[3] *Amer. Journ. Sci.* 1879, p. 499.

parts of the skeleton as in the case of the horse. The metatarsal and metacarpal bones are or are not co-ossified into a cannon bone; the first and second superior incisor teeth are present, rudimentary or wanting, and the premolar number from four to one. The chronological succession of genera is given by Mr. Cope as follows:

	No cannon bone.	Cannon bone present.		
	Incisor teeth present.	Incisors 1 and 2 wanting.		
	4 premolars.	3 premolars.	2 premolars.	1 premolar.
Lower Miocene . .	Poëbrotherium.			
Upper Miocene . .	Protolabis. Procamelus.	Pliauchenia.		
Pliocene and recent .			Camelus.	Auchenia.

According to this table, the Camelidæ have gradually undergone a consolidation of the bones of the feet, with a great reduction in the numbers of the incisor or premolar teeth. Mr. Cope indicates an interesting parallel between the palæontological succession and the embryonic history of the same parts of the skeleton, in the living camel.[1] Among the Carnivora, as M. Gaudry has pointed out, it is not only possible to trace the ancestry of existing species, but to discover traits of union between genera which at present seem far removed.[2]

It is not necessary here to enter more fully into the biological aspect of this great subject. While the doctrine of evolution has now obtained the assent of the great majority of naturalists all over the globe, even the most strenuous upholder of the doctrine must admit that it is attended with palæontological difficulties which no skill or research has yet been able to remove. The problem of derivation remains insoluble, nor perhaps may we hope for any solution beyond one within the most indefinite limits of correctness.[3] But to the palæontologist it is a matter of the utmost importance to feel assured that though he may never be able to trace the missing links in the chain of being, the chain has been unbroken and persistent from the beginning of geological time.

It was remarked above (p. 619) that while the general march of life has been broadly alike all over the world yet progress has been more rapid in some regions and perhaps in some grades of organic being than in others. It has been suggested that the climatic changes which have had so dominant an influence in evolution would affect land plants before they influenced marine animals, and several instances are adduced where an older type of marine fauna is associated with a younger type of terrestrial flora. The flora of Fünfkirchen in Hungary is Triassic in type but occurs in strata which have been classed with the Palæozoic Zechstein. The upper

[1] *American Naturalist*, 1880, p. 172. M. Gaudry traces an analogous process in the foot-bones of the ruminants of Tertiary time, "Les enchainements du Monde Animal," p. 121.
[2] *Op. cit.* p. 210.
[3] A. Agassiz, *Op. cit.* p. 372.

Cretaceous flora of Aix la Chapelle, with its numerous dicotyledons, has a much more modern aspect than the contemporaneous fauna. In the Western Territories of North America much controversy has been raised as to the position of the "Lignitic series," its rich terrestrial flora having an undoubted Tertiary facies, while its fauna is Cretaceous. According to Fuchs the most important turning-point in the history of the plant-world is to be found not, as in the case of the terrestrial fauna, between the Sarmatian stage and the *Congeria*-beds, but on an older horizon, namely between the first and second Mediterranean stage.[1]

From what has now been stated it will be understood that the existence of any living species or genus of plant or animal within a certain geographical area is a fact which cannot be explained except by reference to the geological history of that species or genus. The existing forms of life are the outcome of the evolution which has been in progress during the whole of geological time. From this point of view the investigations of palæontological geology are invested with the profoundest interest, for they bring before us the history of that living creation of which we form a part.

vi. Doctrine of Colonies.—M. Barrande, the distinguished author of the *Système Silurien de la Bohème*, drew attention more than a quarter of a century ago to certain remarkable intercalations of fossils in the series of Silurian strata of Bohemia. He showed that, while these strata presented a normal succession of organic remains, there were nevertheless exceptional bands, which, containing the fossils of a higher zone, were yet included on different horizons among inferior portions of the series. He termed these precursory bands "colonies," and defined the phenomena as consisting in the partial co-existence of two general faunas, which, considered as a whole, were nevertheless successive. He supposed that during the later stages of his second Silurian fauna in Bohemia the first phases of the third fauna had already appeared, and attained some degree of development in some neighbouring but yet unknown region. At intervals, corresponding doubtless to geographical changes, such as movements of subsidence or elevation, volcanic eruptions, &c., communication was opened between that outer region and the basin of Bohemia. During these intervals a greater or less number of immigrants succeeded in making their way into the Bohemian area, but as the conditions for their prolonged continuance there were not yet favourable, they soon died out, and the normal fauna of the region resumed its occupancy. The deposits formed during these partial interruptions, notably graptolitic schists, and calcareous bands, accompanied by igneous sheets, contain, besides the invading species, remains of some of the indigenous forms. Eventually, however, on the final extinction of the second fauna, and, we may suppose, on the ultimate demolition of the physical

[1] E. Weiss, *Neues Jahrb.* 1878, p. 180; also *Z. Deutsch. Geol. Ges.* xxix. p. 252.

barriers hitherto only occasionally and temporarily broken, the third fauna, which had already sent successive colonies into the Bohemian area, now swarmed into it, and peopled it till the close of the Silurian period.[1]

This original and ingenious doctrine has met with much opposition on the part of geologists and palæontologists. Of the facts cited by M. Barrande there has been no question, but other explanations have been suggested for them. It has been said, for example, that the so-called colonies are merely bands of the Upper Silurian rocks or third fauna, which by great plications or fractures have been so folded with the older rocks as to seem regularly interstratified with them,[2] the fossils of the colonies showing little or no mixture of Lower Silurian fossils, such as might have been expected had they been really coeval. But the author of the *Système Silurien* contends that of such foldings or fractures there is no evidence, but that, on the contrary, the sequence of the strata appears normal and undisturbed. Again, it has been urged that the difference of organic contents in these so-called colonies is due merely to a difference in the conditions of water and sea-bottom, particular species appearing with the conditions favourable to their spread, and disappearing when these ceased. But this contention is really included in M. Barrande's theory. The species which disappear and reappear in later stages must have existed in the meanwhile outside of the area of deposit, which is precisely what he has sought to establish. It has been further alleged that no other examples have ever been found of the fauna of one distinct geological formation appearing unmixed in a formation of older date. Much of the opposition which his views have encountered has probably arisen from the feeling that if they are admitted they must weaken the value of palæontological evidence in defining geological horizons. A palæontologist, who has been accustomed to deal with certain fossils as unfailing indications of particular portions of the geological series, is naturally unwilling to see his generalizations upset by an attempt to show that the fossils may occur on a far earlier horizon.

If, however, without entering into the details of the Bohemian instances, we view this question from the broad natural history platform from which it was regarded by M. Barrande, it is impossible not to admit that such phenomena as he has sought to establish in Bohemia must have often occurred in all geological periods and in all parts of the world. No one now believes in the sudden extinction and creation of entire faunas. Every great fauna in the earth's history must have gradually grown out of some pre-existing one, and must have insensibly graduated into that which succeeded.

[1] The doctrine of colonies is developed in the "Système Silurien du centre de la Bohème," 1852, i. p. 73; "Colonies dans le bassin Silurien de la Bohème," in *Bull. Soc. Géol. France* (2nd ser.), xvii. (1859), p. 602; "Défense des Colonies," Prague, i. (1861), ii. (1862), iii. (1865), iv. (1870), v. (1881).

[2] This contention has recently been revived by Mr. J. E. Marr, who has gone over the ground in dispute in Bohemia. *Q. J. Geol. Soc.* Nov. 1880, p. 605.

The occurrence of two very distinct faunas in two closely consecutive series of strata does not prove that the one abruptly died out and the other suddenly appeared in its place. It only shows, as Darwin has so well enforced, the imperfection of the geological record. In the interval between the formation of two such contrasted groups of rocks the fauna of the lower strata must have continued to exist elsewhere, and gradually to change into the newer facies which appeared when sedimentation recommenced with the upper strata. Distinct zoological provinces have no doubt been separated by narrow barriers in former geological periods, as they still are to-day. There seems, therefore, every probability that such migrations as M. Barrande has supposed in the case of the Silurian fauna of Bohemia have again and again taken place.

That examples of these migrations have not been more frequently observed arises doubtless from the inherent imperfection of the geological record and from the difficulty of obtaining the requisite palæontological and stratigraphical data. But that remarkable instances of precursory appearances, apparently complete disappearances, and long subsequent reappearances of fossil forms have been chronicled among the stratified formations can admit of no doubt. One of the most interesting of these may be quoted here from its bearing on the Bohemian evidence of M. Barrande. Among the Lower Silurian rocks of the south of Scotland certain black anthracitic shales have long been known to extend for many miles along the strike of the strata from Moffatdale towards the north-east and south-west. They contain a profusion of graptolites, which, however, are almost wholly confined to these dark bands. The associated grey shales, greywackes, and grits are usually barren of organic remains, but on every horizon of black shales the graptolites reappear. The total maximum thickness of the black-shale group may be from 400 to 500 feet. Over these strata comes a series of massive greywacke, grit, and blue and grey shale, with a thickness of at least 8000 or 10,000 feet, in which hardly any trace of an organism has been met with, though in some of the gritty and calcareous bands encrinites, *petraia*, trilobites, and a few brachiopods have been obtained. Next in succession lies another zone of black shale, in which the same graptolites once more reappear in extraordinary abundance. These organisms could evidently only flourish in the black carbonaceous mud. When the conditions for the deposit of this sediment ceased the graptolites died out in the district, though they continued to live in other areas where they could find their appropriate habitat. No sooner, however, did the dark mud spread once more over the district than the graptolites swarmed in again and re-occupied their former sites. The interval of time represented by the 8000 or 10,000 feet of strata between the two black-shale zones must have been great, if estimated in years, yet it seems to have been accompanied with but little change in the graptolite fauna, though a few species occur in the later which have not been met with in the older zone.[1]

[1] The order of succession of these Silurian strata has been worked out in detail by the officers of the Geological Survey across the whole of the south of Scotland, and has been established by an overwhelming mass of evidence.

Numerous illustrations of the intimate connection between the appearance or reappearance of organic forms and the existence of certain physical conditions are to be found in formations, partly of a fluviatile or estuarine, and partly of marine origin. The Carboniferous Limestone of Scotland furnishes instructive examples. This formation consists of three divisions. The lowest of these contains some thick persistent bands of crinoidal limestone, which with their accompanying shales enclose an abundant marine fauna. The central group consists mainly of sandstones and shales, with numerous seams of coal and ironstone. With a maximum thickness of fully 1500 feet, it contains in abundance the remains of terrestrial vegetation, but the corals, crinoids, producti, spirifers, orthidæ, &c., so profusely developed in the limestones below are entirely absent, while other forms (*anthracosia*, *anthracomya*, *rhizodus*, *gyracanthus*, &c.), either unknown or rare among the limestones, take their place. It certainly might be thought that the older marine fauna had become extinct. Yet that this was not the case is proved by the reappearance of many of the old forms in an upper group of marine limestone forming the highest zone of the series. These organisms had been driven out of the area by a change of conditions, but as soon as these unfavourable conditions passed away, reappeared from some neighbouring region, where they had continued to live and suffer slight modification.[1]

[1] For further illustrations of the early appearance and long survival of species see *postea*, pp. 714, 716, 849.

BOOK VI.

STRATIGRAPHICAL GEOLOGY.

THIS branch of the science arranges the rocks of the earth's crust in the order of their appearance, and interprets the sequence of events of which they form the records. Its province is to cull from the other departments of geology the facts which may be needed to show what has been the progress of our planet, and of each continent and country, from the earliest times of which the rocks have preserved any memorial. Thus from Mineralogy and Petrography it obtains information regarding the origin and subsequent mutations of minerals and rocks. From Dynamical Geology it learns by what agencies the materials of the earth's crust have been formed, altered, broken, or upheaved. From Geotectonic Geology it understands how these materials have been built up into the complicated crust of the earth. From Palæontological Geology it receives in well-determined fossil remains a clue by which to discriminate the different stratified formations, and to trace the grand onward march of organized existence upon the planet. Stratigraphical geology thus gathers up the sum of all that is made known by the other departments of the science, and makes it subservient to the interpretation of the geological history of the earth.

The leading principles of stratigraphy may be summed up as follows:

1. In every stratigraphical research the fundamental requisite is to establish the order of superposition of the strata. Until this is accomplished it is impossible to arrange the relative dates and make out the sequence of geological history.

2. The stratified portion of the earth's crust, or Geological Record, may be subdivided into natural groups or formations of strata, each marked throughout by some common genera or species of organic remains, or by a general resemblance in their palæontological type or character.

3. Living species of plants and animals can be traced downward into the more recent geological formations; but grow fewer in number as they are followed into more ancient deposits. With their disappearance we encounter other species and genera which are no longer living. These in turn may be traced backward into earlier

formations, till they too cease, and their places are taken by yet older forms. It is thus shown that the stratified rocks contain the records of a gradual progression of organic types. A species which has once died out does not seem ever to have reappeared. But as has been already pointed out in reference to Barrande's doctrine of colonies, a species may within a limited area appear in a formation older than that of which it is elsewhere characteristic, having temporarily migrated into the district from some neighbouring region where it had already established itself.

4. When the order of succession of organic remains among the stratified rocks has once been accurately determined, it becomes an invaluable guide in the investigation of the relative age and structural arrangements of rocks. Each zone or group of strata, being characterized by its own species or genera, may be recognized by their means, and the true succession of strata may thus be confidently established even in a country wherein the rocks have been greatly fractured, folded, or inverted.

5. The relative chronological value of the divisions of the Geological Record is not to be measured by mere depth of strata. While a great thickness of stratified rock may be reasonably assumed to mark the passage of a long period of time, it cannot safely be affirmed that a much less thickness elsewhere represents a correspondingly diminished period. The truth of this statement may sometimes be made evident by an unconformability between two sets of rocks, as has already been explained. The total depth of both groups together may be, say 1000 feet. Elsewhere we may find a single unbroken formation reaching a depth of 10,000 feet; but it would be utterly erroneous to conclude that the latter represents ten times the duration indicated by the two former. So far from this being the case, it might not be difficult to show that the minor thickness of rock really denoted by far the longer geological interval. If, for instance, it could be proved that the upper part of both the sections lay on one and the same geological platform, but that the lower unconformable series in the one locality belonged to a far lower and older system of rocks than the base of the thick conformable series in the other, then it would be clear that the gap marked by the unconformability really indicated a longer period than the massive succession of deposits.

6. Fossil evidence furnishes the chief means of comparing the relative chronological value of groups of rock. A break in the succession of organic remains marks an interval of time often unrepresented by strata at the place where the break is found. The relative importance of these breaks, and therefore, probably, the comparative intervals of time which they mark, may be estimated by the difference of the facies of the fossils on each side. If, for example, in one case we find every species to be dissimilar above and below a certain horizon, while in another locality only half of the

species on each side of a band are peculiar, we naturally infer, if the total number of species seems large enough to warrant the inference, that the interval marked by the former break was very much longer than that marked by the latter. But we may go further and compare by means of fossil evidence the relation between breaks in the succession of organic remains and the depth of strata between them.

Three series of fossiliferous strata, A, C, and H, may occur conformably above each other. By a comparison of the fossil contents of all parts of A, it may be ascertained that, while some species are peculiar to its lower, others to its higher portions, yet the majority extend throughout the group. If now it is found that of the total number of species in the upper portion of A only one-third passes up into C, it may be inferred with some probability that the time represented by the break between A and C was really longer than that required for the accumulation of the whole of the group A. It might even be possible to discover elsewhere a thick intermediate group B filling up the gap between A and C. In like manner were it to be discovered that, while the whole of the group C is characterized by a common suite of fossils, not one of the species and only one half of the genera pass up into H, the inference could hardly be resisted that the gap between the two groups marks the passage of a far longer interval than was needed for the deposition of the whole of C. And thus we reach the remarkable conclusion that, thick though the stratified formations of a country may be, in some cases they may not represent so long a total period of time as do the gaps in their succession,—in other words, that non-deposition has been in some areas more frequent and prolonged than deposition, or that the intervals of time which have been recorded by strata have sometimes not been so long as those which have not been so recorded.

In all speculations of this nature, however, it is necessary to reason from as wide a basis of observation as possible, seeing that so much of the evidence is negative. Especially needful is it to bear in mind that the cessation of one or more species at a certain line among the rocks of a particular district may mean nothing more than that, owing to some change in the conditions of life or of deposition, these species were compelled to migrate, or became locally extinct at the time marked by that line. They may have continued to flourish abundantly in neighbouring districts for a long period afterward. Many examples of this obvious truth might be cited. Thus in a great succession of mingled marine, brackish-water, and terrestrial strata, like that of the Carboniferous Limestone series of Scotland, corals, crinoids, and brachiopods abound in the limestones and accompanying shales, but grow fewer or disappear in the sandstones, ironstones, clays, coals, and bituminous shales. An observer meeting for the first time with an instance of this disappearance, and remembering what he had read about "breaks in

succession," might be tempted to speculate about the extinction of these organisms, and their replacement by other and later forms of life, such as the ferns, lycopods, ganoid fishes, and other fossils so abundant in the overlying strata. But further research would show him that, high above the plant-bearing sandstones and coals, other limestones and shales might be observed, charged with the same marine fossils as before, and still further overlying groups of sandstones, coals, and carbonaceous beds followed by yet higher marine limestones. He would thus learn that the same organisms, after being locally exterminated, returned again and again to the same area. Such a lesson would probably teach him to pause before too confidently asserting that the highest bed in which certain fossils can be detected, marks really their final appearance in the history of life. An interruption in the succession of fossils may thus be merely temporary or local, one set of organisms having been driven to a different part of the same region, while another set occupied their place until the first was enabled to return.

7. The Geological Record is at the best but an imperfect chronicle of the geological history of the earth. It abounds in gaps, some of which have been caused by the destruction of strata owing to metamorphism, denudation, or otherwise, some by original non-deposition, as above explained. Nevertheless it is from this record that the progress of the earth is chiefly traced. It contains the registers of the births and deaths of tribes of plants and animals which have from time to time lived on the earth. Probably only a small proportion of the total number of species which have appeared in past time have been thus chronicled, yet by collecting the broken fragments of the record an outline at least of the history of life upon the earth can be deciphered.

It cannot be too frequently stated, nor too prominently kept in view, that, although gaps occur in the succession of organic remains as recorded in the rocks, there have been no such blank intervals in the progress of plant and animal life upon the globe. The march of life has been unbroken, onward and upward. Geological history, therefore, if its records in the stratified formations were perfect, ought to show a blending and gradation of epoch with epoch, so that no sharp divisions of its events could be made. But the record of the history has been constantly interrupted; now by upheaval, now by volcanic outbursts, now by depression, now by protracted and extensive denudation. These interruptions serve as natural divisions in the chronicle, and enable the geologist to arrange his history into periods. As the order of succession among stratified rocks was first made out in Europe, and as many of the gaps in that succession were found to be widespread over the European area, the divisions which experience established for that portion of the globe came to be regarded as typical, and the names adopted for them were applied to

the rocks of other and far distant regions. This application has brought out the fact that some of the most marked geological breaks in Europe do not exist elsewhere, and, on the other hand, that some portions of the record are much more complete there than in other regions. Hence, while the general similarity of succession may remain, different subdivisions and nomenclature are required as we pass from continent to continent.

A bed, or limited number of beds, characterized by one or more distinctive fossils, is termed a zone or horizon, and, as already mentioned, is often known by the name of a typical fossil, as the different zones in the Lias are by their special species of ammonite. Two or more such zones, united by the occurrence in them of a number of the same characteristic species or genera, may be called beds or an assise, as in the "Micraster beds or assise" of the Cretaceous system, which include the zones of *M. cor-testudinarium* and *M. cor-anguinum*. Two or more sets of such connected beds or assises may be termed a group or stage (étage). A number of groups or stages similarly related constitute a series, section (Abtheilung), or formation, and a number of series, sections, or formations may be united into a system.[1]

The nomenclature adopted for these subdivisions bears witness to the rapid growth of geology. It is a patch-work in which no uniform system nor language has been adhered to, but where the influences by which the progress of the science has been moulded may be distinctly traced. Some of the earliest names are lithological, and remind us of the fact that mineralogy and petrography

[1] The unification of geological nomenclature throughout the world is one of the objects aimed at by the recently instituted "International Geological Congress," which at its late meeting at Bologna recommended the adoption of the following terms, the most comprehensive being placed first:

Divisions of sedimentary formations.	*Corresponding chronological terms.*
Group.	Era.
System.	Period.
Series.	Epoch.
Stage.	Age.

As equivalents of *Series*, the terms *Section* or *Abtheilung* may be used; as a subdivision of stage, the words *Beds* or *Assise*.

"According to this scheme," Mr. Topley, one of the secretaries, remarks, "we would speak of the Palæozoic Group or Era, the Silurian System or Period, the Ludlow Series or Epoch, and the Aymestry Stage or Age. The term 'formation' raises a difficulty, because this word is used by English geologists in a sense unknown abroad. To bring our nomenclature into conformity with that of other nations it will be necessary to use the word only as descriptive of the mode of formation, or of the material composing the rock. We may speak of the 'Carboniferous Formation' as a group of beds containing coal: but not as a name for a set of rocks apart from the mineral contents. In like manner, we may speak of the 'Chalk Formation' but not of the 'Cretaceous Formation.'" (*Geol. Mag.* 1881, p. 557.) It may be doubted whether the recommendations of any congress, international or other, will be powerful enough to alter the established usages of a language. The term *group* has been so universally employed in English literature for a division subordinate in value to *series* and *system* that the attempt to alter its significance would introduce far more confusion than can possibly arise from its retention in the accustomed sense.

preceded geology in the order of birth—Chalk, Oolite, Greensand, Millstone Grit. Others are topographical, and bear witness to the localities where formations were first observed, or are typically developed—Oxfordian, Portlandian, Kimeridgian, Jurassic, Rhætic, Permian, Neocomian. Others are taken from local English provincial names, and remind us of the special debt we owe to William Smith, by whom so many of them were first used—Lias, Gault, Crag, Cornbrash. Others recognize an order of superposition as already established among formations—Old Red Sandstone, New Red Sandstone; while still another class is founded upon numerical considerations—Dyas, Trias. By common consent it is admitted that names taken from the region where a formation or group of rocks is typically developed, are best adapted for general use. Cambrian, Silurian, Devonian, Permian, Jurassic, are of this class, and have been adopted all over the globe.

But whatever be the name chosen to designate a particular group of strata, it soon comes to be used as a chronological or homotaxial term, apart altogether from the lithological character of the strata to which it is applied. Thus we speak of the Chalk or Cretaceous system, and embrace under that term formations which may contain no chalk; and we may describe as Silurian a series of strata utterly unlike in lithological characters to the formations in the typical Silurian country. In using these terms we unconsciously adopt the idea of relative date. Hence such a word as Chalk or Cretaceous does not so much suggest to the geologist the group of strata so called, as the interval of geological history which these strata represent. He speaks of the Cretaceous, Jurassic, and Cambrian periods, and of the Cretaceous fauna, the Jurassic flora, the Cambrian trilobites, as if these adjectives denoted simply epochs of geological time.

The Geological Record is classified into five main divisions:—(1) the Archæan, sometimes called Azoic (lifeless), or Eozoic (dawn of life); (2) the Palæozoic (ancient life) or Primary; (3) the Mesozoic (middle life) or Secondary; (4) the Cainozoic (recent life) or Tertiary, and (5) the Post-Tertiary or Quaternary. These divisions are further ranged into systems, each system into series, sections, or formations, each formation into groups or stages, and each group into single zones or horizons. The following generalized table exhibits the order in which the chief subdivisions appear.

THE GEOLOGICAL RECORD,

OR, ORDER OF SUCCESSION OF THE STRATIFIED FORMATIONS OF THE EARTH'S CRUST.

	Europe.	North America.	India and adjacent regions.	New Zealand.
[Qu]ARNARY OR TERTIARY.	**Recent and Pre-historic**—alluvium of rivers, lakes, and seas; peat, shell-beds, &c. Younger raised-beaches, kitchen-middens, lake-dwellings, &c. Neolithic and Palæolithic deposits.	Recent.	Recent and Post-tertiary alluvium.	Recent.
	Pleistocene (Diluvium)—cave deposits, Loess, older valley-	Champlain—old terraces (ma-	Laterite	Pleistocene
PRIMARY OR PALÆOZOIC.	**Carboniferous.** Coal Measures—Terrain houiller, Steinkohlenformation. Millstone Grit—Flötzleerer Sandstein. Carboniferous Limestone Series—Calcaire Carbonifère, Kohlenkalk, Kulm.	Coal-Measures, Carboniferous. Sub-carboniferous.	Godwana system	?Kaikoura formation.
	Devonian and Old Red Sandstone. Devonian. Upper—Cypridina and Goniatites beds. Middle—Stringocephalus (Eifel) Limestone. Lower—Spirifer Sandstone, &c. Old Red Sandstone. Upper yellow and red sandstones with *Holoptychius*. Lower sandstones and flagstones with *Cephalaspis*, *Coccosteus*, &c.	Both the Devonian and Old Red Sandstone types are developed in the eastern regions of Canada and the United States.	Vindhyan System. [Carboniferous and Silurian in Salt Range.]	? Kakanui.[1] Waihao. Wanaka formation.
	Silurian—Transition or Greywacke. Upper. Ludlow group. Wenlock „ Upper Llandovery group. Lower. Lower Llandovery group. Caradoc and Bala „ Llandeilo „ Arenig „	Silurian. Upper. Oriskany formation. Lower Helderberg group. Salina group. Niagara group. Lower. Cincinnati, Utica, and Trenton groups. Chazy, Quebec, and Calciferous groups.	Transition or sub-metamorphic.	
	Cambrian—Primordial. Upper. Tremadoc slates. Lingula flags. Lower. Menevian group. Harlech and Longmynd group.	Potsdam formation. Acadian „		
	Archæan (Precambrian). Primitive schists, gneiss and other crystalline rocks.	Huronian. Laurentian.	Gneiss, &c.	Gneiss, &c.

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PART I.—ARCHÆAN.

§ 1. General Characters.

From underneath the most ancient fossiliferous stratified formations there rises to the surface in many parts of the globe a series of thoroughly crystalline schists and massive rocks. These fundamental formations have been regarded by some writers as portions of the primeval crust of the globe—traces of the surface that first congealed upon the molten nucleus. They are regarded by others as probably metamorphosed sediments which may belong to many different periods of geological history. Apart from the disputed question of their origin, they are everywhere acknowledged to include the oldest known rocks. Hence in so far as geological history is recorded in rock-formations they must be taken as its starting-point. In attempting to fix their relative date we first observe that they lie unconformably below succeeding formations. But this relation obviously goes only a short way in establishing their chronology. Nor are lithological characters much more valuable for the purpose. It must be conceded that these rocks may have originated at many widely separated periods of early geological time, but that as yet no means have been devised of establishing any generally applicable tests of their relative antiquity. Hence for want of any satisfactory means of discrimination, these ancient crystalline masses must be, at least provisionally, classed under one common name. They were formerly, and are still by some writers, called Primitive; but the term Archæan, first proposed by Dana, has been generally adopted for them both in America and in Britain.

Archæan rocks everywhere present the same general characters. For the most part they consist of gneiss in many varieties, passing into various schists, among which occur subordinate bands of hornblendic and pyroxenic rocks, limestone, dolomite, serpentine, quartzite, graphite, hæmatite, magnetite, &c. The rocks have a general stratified structure, but the individual beds often present great irregularities of thickness, being specially prone to a lenticular development. Occasionally they dip continuously for some distance at angles of 40° or less; but more usually they are greatly plicated, and sometimes exhibit the most extraordinarily complex puckerings. The gneiss shades off into a non-foliated rock which occurs with it in alternating bands, but is in structure a true granite. Occasionally bands of this granite wander across the foliation of the gneiss. But they evidently belong to the period and processes of the gneiss formation, and cannot be classed as later intrusive eruptions. Everywhere the various bands of gneiss, and inter-stratified layers of schist or other crystalline rock are intimately united to each other by a minute felting together of their component crystals.

Though no general order of succession has been observed among Archæan rocks, there is usually a difference between the texture of the lower and upper parts. The former are commonly coarser and more granitoid. They consist mainly of gneiss, with bands and veins of granite. The upper portions, less coarsely crystalline, are composed of mica-schists, talc-schists, chlorite-schists, and clay-slates, among which veins of granite and other crystalline massive rocks are less frequent. In Central Europe there appears to be a gradation from the lowest up into the latest portion of the thick Archæan series. In Canada, however, a marked line of unconformability exists between the gneisses (Laurentian) and the overlying slates, conglomerates, quartzites, and limestones (Huronian). Logan even traced an unconformability between the lower and upper part of the gneiss. The occurrence of occasional bands of coarse conglomerate among the Archæan rocks in different countries, especially in Canada, where they occur among the limestones and schists, points to elevation of land, and littoral erosion during the formation of these rocks.

The analogies between the structure of Archæan rocks and that of crystalline schists which have been produced by the metamorphism of ordinary sedimentary formations have been already pointed out (Book IV. Part VIII.). The Archæan gneisses and schists are distinctly bedded, and their alternations of schists, quartzites, and marbles, closely resemble those of the shales, sandstones, and limestones of younger geological periods. The conglomerates above alluded to furnish unquestionable evidence of an original clastic structure in some of the strata. The grains, streaks, layers, and thicker zones of graphite in the gneiss remind the observer of the way in which coaly matter is diffused through the sandstones and shales of the Coal-measures. Hence it is difficult to avoid the inference, that these ancient crystalline rocks represent former marine sediments.

In one of the Archæan (Laurentian) limestones of Canada, specimens have been found of a remarkable mixture of calcite and serpentine. These minerals are arranged in alternate layers, the calcite forming the main framework of the substance, with the serpentine (sometimes loganite, pyroxene, &c.) disposed in thin, wavy, inconstant layers, as if filling up flattened cavities in the calcareous mass. So different from any ordinary mineral segregation with which he was acquainted did this arrangement appear to Logan, that he was led to regard the substance as probably of organic origin. This opinion was adopted, and the structure of the supposed fossil was worked out in detail by Dr. Dawson of Montreal, who pronounced the organism to be the remains of a massive foraminifer which he called *Eozoon*, and which he believed must have grown in large thick sheets over the sea-bottom. This opinion was confirmed by Dr. W. B. Carpenter, who, from additional and better preserved specimens, described a system of internal canals having the characters

of those in true foraminiferal structures. Other observers, notably Professors King and Rowney of Galway and Möbius of Kiel, have opposed the organic nature of *Eozoon*, and have endeavoured to show that the supposed canals and passages are merely infiltration veinings of serpentine in the calcite. In some cases, however, the "canal-system" is not filled with serpentine but with dolomite, which seems to prove that the cavities must have existed before either dolomite or serpentine was introduced into the substance. Dr. Carpenter contends that the disposition of these passages in his decalcified specimens is very regular, and quite unlike any mineral infiltration with which he is acquainted. In the Archæan rocks of Bohemia and Bavaria specimens were some years ago obtained showing a structure like that of the Canadian Eozoon. They were accordingly described as of organic origin, under the respective names of *Eozoon Bohemicum* and *E. Bavaricum*. But their true mineral nature appears to be now generally admitted.

The opinion of the organic nature of *Eozoon* has been supposed to receive support from the large quantity of graphite found throughout the Archæan rocks of Canada and the northern parts of the United States. This mineral occurs partly in veins, but chiefly disseminated in scales and laminæ in the limestones and as independent layers. Dr. Dawson estimates the aggregate amount of it in one band of limestone in the Ottawa district as not less than from 20 to 30 feet, and he thinks it is hardly an exaggeration to say that there is as much carbon in the Laurentian as in equivalent areas of the Carboniferous system. He compares some of the pure bands of graphite to beds of coal, and maintains that no other source for their origin can be imagined than the decomposition of carbon dioxide by living plants. In the largest of three beds of graphite at St. John he has found what he considers may be fibrous structure indicative of the existence of land-plants.

Still further evidence in favour of organized existence during Archæan time in the North American area has been adduced from the remarkably thick and abundant masses of iron-ore associated with the Laurentian rocks of Canada and the United States. Dr. Sterry Hunt has called attention to these ores as proving the precipitation of iron by decomposing vegetation during the Laurentian period on a more gigantic scale than at any subsequent geological epoch.[1] Some of the beds of magnetic iron range up to 200 feet in thickness. Large masses also of hæmatite and titaniferous iron, as well as of iron sulphides, occur in the Canadian Archæan series.

Besides the granitic and other veins and bands which are so intimately associated especially with the older and more crystalline portions of the Archæan rocks, there have been noticed, in the younger portions, more or less satisfactory traces of contemporaneous volcanic action. In the iron regions of Lake Superior beds of

[1] "Geology of Canada," 1863, p. 573.

crystalline diabase are intercalated with the Huronian quartzites. In various localities in Wales and England what have been described as rhyolitic lavas and coarse agglomerates occur in supposed insular areas of Archæan rocks.

Among masses so thoroughly crystalline in structure, crystalline minerals, as may be expected, are specially abundant. Among these may be mentioned hornblende, actinolite, tremolite, pyroxene, vesuvianite, serpentine, kyanite, graphite, garnet, epidote, apatite, tourmaline, wollastonite, zircon, fluor-spar, pyrite, chalcopyrite, magnetite, titaniferous iron, and hæmatite. Some of these minerals (iron-ores, hornblende, apatite) occasionally form massive lenticular bands as well as run in a diffused form through the limestone or gneiss. Certain regions (Sweden, Erzgebirge, &c.) abound in veins of metallic ores—gold, silver, copper, lead, &c.

The largest areas of Archæan rocks now exposed at the surface are in the northern parts of Europe and North America. Elsewhere they rise as isolated insular spaces surrounded with younger formations.

§ 2.—Local Development.

Britain.—In no part of the European area are these ancient rocks better seen than in the north-west of Scotland. Their position there, previously indicated by Macculloch and Hay Cunningham, was first definitely established by Murchison, who showed that they possess a dominant strike to N.N.W., and are unconformably overlaid by all the other rocks of the Scottish Highlands. (See Fig. 300.) They form nearly the whole of the Outer Hebrides, and occupy a variable belt of the western parts of the counties of Sutherland and Ross. Murchison proposed to term them the Fundamental or Lewisian Gneiss from the isle of Lewis—the chief of the Hebrides. Afterwards he called them Laurentian, regarding them as the equivalent of some part of the great Laurentian system of Canada. They consist of a tough massive gneiss usually hornblendic, with bands of hornblende-rock, hornblende-schist, actinolite-schist, eclogite, mica-schist, sericite-schist, and other crystalline rocks. In two or three places they enclose bands of limestone, but neither in these nor in any other parts of their mass has the least trace of any organic structure been detected. In traversing the western sea-board, from Cape Wrath to Loch Torridon, I have ascertained that these ancient rocks are disposed in several broad anticlinal and synclinal folds, the angles of dip often not exceeding from 30° to 40°, and the strata succeeding each other with unexpected regularity, though here and there showing great local crumpling. The lower portions of the series are on the whole more massive than the upper, and more traversed by pegmatite veins. Between Loch Laxford and Cape Wrath this lower division has a distinctly pinkish tint from the colour of its abundant orthoclase, and the number and size of its pegmatite veins. Some of the lowest bands of the formation may be observed along an anticlinal fold north of Loch Inver, where one of the most conspicuous rocks is an unctuous sericitic schist. The upper division cannot be sharply defined, but is on the whole marked by the relative thinness of its beds,

with a much larger development of schists, and a great diminution in the quantity of pegmatite—characters particularly well seen at Gairloch. No satisfactory estimate has yet been made of the probable thickness of these rocks. On the lowest calculation it must amount to at least 20,000 feet.

Several features in the structure of this gneiss deserve attention. The pegmatite has been described as an intrusive granite traversing the gneiss in veins. In many cases, it is true, this rock looks as if it had been forcibly injected, for the foliation of the gneiss is abruptly bent up on either side of the pegmatite. But besides the difficulty of conceiving that the coarsely crystalline materials of these veins ever could have been in such a state of igneous fusion or aquo-igneous plasticity as to be capable of being injected into rents of the surrounding rock, there are some characteristics which seem to make it nearly certain that the pegmatite belongs to the same series of crystalline processes by which the gneiss itself was produced. The same mass of pegmatite may be observed in one place regularly interbedded with the gneiss (Fig. 315), and at another place traversing it in different directions (Fig. 316). But in both conditions there is the most intimate crystalline union of the pegmatite with the gneiss, the crystals of each rock dovetailing into each other. Here and there, too, the crumpled folia of gneiss pass into pegmatite, in which a rude crumpled foliation may be detected. At Cape Wrath, alternate thin layers of gneiss and pegmatite occur with as perfect regularity and as insensible gradations of structure as among the ordinary folia in any part of the gneiss (Fig. 315). But one of the

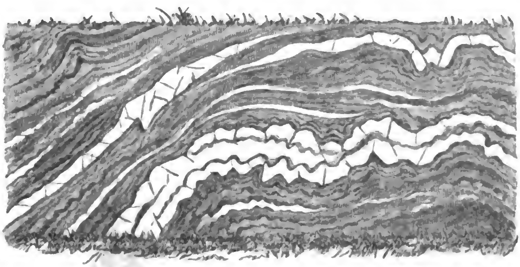

FIG. 315.—GNEISS WITH INTERSTRATIFIED BANDS OF PEGMATITE, CAPE WRATH.

most singular facts remains to be noticed. In a number of examples from Cape Wrath to Loch Laxford I have observed that in pegmatite veins which cut across the gneiss, a rude foliation has been developed, parallel in a general sense to that of the gneiss on either side (Fig. 317). Such cases suggest that the pegmatite veins were produced before the process of foliation in the surrounding rock was completed, so that the materials of the veins were to some extent affected by its later stages.

Another conspicuous feature, especially of the lower massive gneiss, is the occurrence of geodes and lenticular bands or layers of black hornblende or of a mixture of hornblende with a little felspar or quartz, less

commonly black mica. Kernels of this nature, a foot or more in diameter, may be observed on Loch Torridon, consisting of massive cleavable hornblende. At this locality also some good examples occur of a structure in the gneiss where certain laminæ display a remarkable

Fig. 316.—Veins of Pegmatite in Gneiss, near Cape Wrath.

puckering between parallel, not contorted beds (Fig. 318), a structure which may be compared with that of many sands and sandstones (*ante*, p. 479). Everywhere the closest union may be traced between the

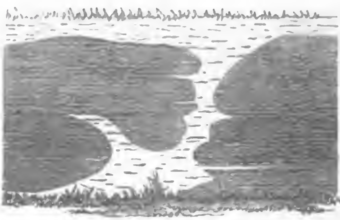

Fig. 317.—Foliation of a Pegmatite Vein in Gneiss, Loch Laxford.

gneiss and the parallel bands of pegmatite, granite, syenite, and other massive rocks inter-stratified with it, as if these were not of subsequent origin, but were contemporaneously-formed parts of the gneiss.

Recent observations by Professor Hull and Messrs. Symes and Wilkin-

son, of the Geological Survey of Ireland, have shown that in Donegal there exists a massive granitic gneiss which they identify with the fundamental gneiss of the north-west of Scotland, and which they find to be covered unconformably by the quartzites, limestones, and other crystalline rocks, that were shown by Harkness to be continuations of the similar series of Lower Silurian masses in the Scottish Highlands. The characteristic red Cambrian sandstone of the later region, however, has not been detected in Ireland.[1]

In England and Wales certain isolated tracts of crystalline rocks have been recently referred by Dr. Hicks,[2] Professor Bonney,[3] and others to a pre-Cambrian age. Beneath the fossiliferous Cambrian strata of St. David's certain crystalline masses appear in which, according to Dr. Hicks, there is a lower group (Dimetian) consisting of quartzose and granitoid rocks, including coarse gneiss, bands of impure limestone or dolomite, schists, and dolerites; a middle group (Arvonian) composed essentially of contemporaneous volcanic rocks, rhyolitic felsites, volcanic breccias and hälleflintas or felsitic tuffs, forming, with the foregoing

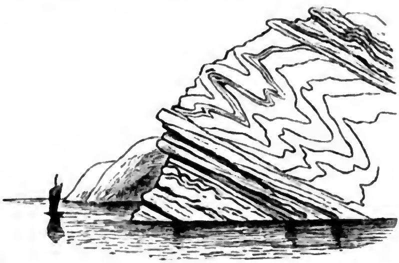

FIG. 318.—PUCKERED LAMINÆ BETWEEN PARALLEL BANDS OF GNEISS, LOCH TORRIDON.

group, a total nearly 15,000 feet thick; and an upper group (Pebidian) made up of slaty and comparatively little altered rocks, and fully 3000 feet thick. In North Wales and Anglesea other areas of crystalline rock have been assigned to a similar geological position. Professor Bonney has described some of the masses as true lavas having so perfect a rhyolitic structure that they might almost be classed with recent rhyolites, and as being of contemporaneous origin with the rocks among which they lie, for fragments derived from them are abundant in the strata overlying them up to the base of the Cambrian series. On the other hand, Professor Ramsay believes that the so-called "Pre-Cambrian" areas are only highly metamorphosed portions of the Cambrian rocks with associated igneous intrusions.[4] Again, in the

[1] *Geol. Mag.* 1881, p. 506. Kinahan, *Op. cit.* p. 427. Hull, *Trans. Roy. Dublin Soc.* i. (2nd. ser.), 1882, p. 243.

[2] *Quart. Journ. Geol. Soc.* xxxiii. pp. 229; xxxiv. p. 285, 295. *Geol. Mag.* 1879, p. 433.

[3] *Quart. Journ. Geol. Soc.* xxxiv. p. 144; xxxv. pp. 305, 309, 321. Hughes, *Op. cit.* xxxiv. p. 137; xxxv. p. 682; xxxvi. p. 237.

[4] *Mem. Geol. Survey*, vol. iii., "Geology of North Wales." Dr. Callaway (*Q. J. Geol. Soc.* xxxvii. p. 210) has described the gneissic and slaty rocks of Anglesea as Archæan.

Malvern Hills, a ridge of crystalline hornblendic rocks has been classed as of Pre-Cambrian date.[1] In the Wrekin Mr. Allport[2] has found a nucleus of rhyolitic lava with rhyolitic agglomerate underlying quartzite, which according to Dr. Callaway is older than the Lingula Flags.[3] Ancient as these volcanic masses are, they present remarkably perfect spherulitic and perlitic structures. Lastly, from amid the Triassic plains of Leicestershire rises an insular area of rocky hills composed of various crystalline rocks, which by the Geological Survey have been classed as altered Cambrian, by Messrs. Hill and Bonney as probably of pre-Cambrian date.[4] They consist of three great groups, among which volcanic agglomerates and tuffs form a large part. It will be observed that in all these tracts of presumed Archæan rocks in England and Wales, lavas and volcanic detrital masses are especially prominent. No evidence of any contemporaneous volcanic materials has yet been detected in the extensive Archæan tracts of Scotland.

Scandinavia.—In Scandinavia,[5] Archæan rocks (Grundfjeldet, Urgebirge) occupy extensive areas. They consist chiefly of gneiss, but include also quartzite, quartz-conglomerate, quartz-schist, hornblende-schist, mica-schist, limestone, dolomite, with granite, pegmatite, amphibolite, garnet-rock, syenite, gabbro, labradorite-rock, olivine-rock, serpentine, &c. No general order of succession has yet been determined, though a clear arrangement into distinct zones is in many places observable. Thus in Rukedal (Southern Norway) a mass, 3900 feet thick, of quartzite, quartz-schist and interbedded seams of hornblende-schist, lies upon a group of hornblende-schists and grey gneiss traversed by abundant granite veins. Thin bands of limestone occasionally occur in the gneiss, as near Christiansand, where they have yielded many minerals, especially vesuvianite, coccolite, scapolite, phlogopite, chondrodite, and black spinel. Apatite with magnetite, titaniferous iron, hæmatite, and other ores forms a marked feature of the Norwegian Archæan series. The same rocks range into Sweden, where a red gneiss is found in the western, and a grey gneiss in the eastern districts. The former has been observed overlying the latter. The youngest division of the series consists of fine-grained to compact eurites or hälleflintas, with bands of crystalline limestone. Granite and other eruptive rocks abound. The most important mineral masses in an industrial sense are thick beds and lenticular masses of iron-ore (Dannemora, Filipstad, &c.).

Central Europe.—From Scandinavia rocks presumed to be Archæan range through Finland into the north-west of Russia, reappearing in the north-east of that vast empire in Petchora Land down to the White Sea, and rising in the nucleus of the chain of the Ural Mountains, and still further south in Podolia. In Central Europe they appear as islands in the midst of more recent formations. Among the Carpathian Mountains they pro-

[1] Holl, *Quart. Journ. Geol. Soc.* xxi. p. 72.

[2] *Op. cit.* xxxiii. p. 449.

[3] *Op. cit.* xxxiv. p. 754; xxxv. p. 643; xxxvi. p. 536.

[4] Hill and Bonney, *Q. J. Geol. Soc.* xxxiii. p. 754; xxxiv. p. 199; xxxvi. p. 337.

[5] Keilhan, "Gaea Norvegica," iii. (1850). Kjerulf, "Udsigt over det Sydlige Norges Geologi," Christiania, 1879 (translated into German by Gurlt, and published by Cohen, Bonn, 1880). A. E. Törnebohm, "Die Schwedischen Hochgebirge," *Schwed. Akad.* Stockholm, 1873. "Das Urterritorium Schwedens," *Neues Jahrb.* 1874, p. 131. Karl Pettersen, Geologiske Undersögelser inden Tromsö Amt, &c., *Norske Videnskab. Skrift*, vi. 44; vii. 261.

trude at a number of points. Westwards of the central portion of the Alpine chain they rise in a more continuous belt, and show numerous mineralogical varieties, including protogine, mica-schist, and many other schists, as well as limestone and serpentine. But their most compact area, and most intelligible sections are to be found in the region that extends southward from Dresden through Bavaria and Bohemia between the valley of the Danube and the headwaters of the Elbe. They are there divided into two well-marked groups—(*a*) red gneiss, containing pink orthoclase and a little white potash-mica, covered by (*b*) grey gneiss, containing white or grey felspar, and abundant dark magnesia-mica. According to Gümbel the former (called by him the Bojan gneiss) may be traced as a distinct formation associated with granite, but with very few other kinds of crystalline or schistose rocks, while the latter (termed the Hercynian gneiss) consists of gneiss with abundant interstratifications of many other schistose rocks, graphitic limestone, and serpentine. The Hercynian gneiss is overlaid by mica-schist, above which comes a vast mass of argillaceous schists and shales. In Bohemia these overlying crystalline clay-slates, and schists (Etage A of Barrande) graduate upward into undoubted clastic rocks known as the Príbram shales, unconformably over which come conglomerates and sandstones lying at the base of the fossiliferous series.[1] In the Pyrenees the existence of Pre-Cambrian granites, with associated well-stratified masses of gneiss, mica-schist, limestone, &c., has been determined.[2]

America.—In North America Archæan rocks cover a large part of the continent from the Arctic Circle southwards to the great lakes. In Canada, where they were studied in detail by Logan, they consist of two divisions. The lower of these, termed *Laurentian*, from its abundant development along the shores of the St. Lawrence, was estimated by him to be about 30,000 feet thick, but neither its top nor base has been seen. It has been divided into two series—(1) a lower formation more than 20,000 feet thick, consisting chiefly of granite, orthoclase gneiss, bands of quartz-rock, schists, iron-ore, and limestone containing the *Eozoon* above referred to; and (2) an upper formation fully 10,000 feet thick, composed also, for the most part, of gneiss, but marked by the occurrence of bands of Labrador felspar, as well as schist, iron-ore, and limestone. The upper division has been stated to lie unconformably on the lower. Mr. Selwyn, however, has recently contended that the limestone-bearing series rests conformably upon a massive granitoid gneiss, to which he would restrict the term Laurentian, classing the limestones in the next or Huronian system.[3]

Above the Laurentian rocks in the region of Lake Huron lies a vast mass of slates, conglomerates, limestones, and quartz-rocks, attaining a depth of from 10,000 to 20,000 feet. They are termed *Huronian*. No

[1] The following references to descriptions of the Archæan rocks of Central Europe may be useful. Saxony, &c., Credner, *Zeitsch. Deutsch. Geol. Ges.* 1877, p. 757. Explanations accompanying the sheets of the Geological Survey Map of Saxony, particularly sections Geringswalde, Geyer, Glauchau, Hohenstein, Penig, Rochlitz, Waldheim. Bavaria and Bohemia, Gümbel, Geognostische Beschreibung des Ostbayerischen Grenzgebirges, Gotha, 1868; Jokely, *Jahrb. Geol. Reichsanstalt.* vi. p. 355; viii. p. 1, 516; Kalkowsky, "Die Gneissformation des Eulengebirges" (Habilitationschrift), Leipzig (Engelmann), 1878.

[2] Garrigou, *Bull. Soc. Géol. France*, i. (1873), p. 418.

[3] *Nat. Hist. Soc.*, Montreal, February, 1879.

fossils have yet been found in them; but they must be much younger than the Laurentian rocks, on which they rest unconformably, and from which they have been in part at least derived.

Crystalline gneisses, schists, and other associated rocks occur, as in Europe, in the cores of many of the chief mountain ranges of North America, and have with more or less confidence been assigned to the Archæan series, for example, in the Appalachian chain, and in many of the separate ranges comprised among the Rocky Mountains. It is probable, however, that some of the rocks included in this reference are metamorphic rocks of much later date. In the Wahsatch Mountains, Utah, certain granites, included as Archæan, have been shown to be younger than the Carboniferous period.[1]

India.—In India the oldest known rocks are gneisses which underlie the most ancient Palæozoic formations, and appear to belong to two periods. The older or Bundelkund gneiss is covered unconformably by certain "transition" or "submetamorphic" rocks, which, as they approach the younger gneiss, become altered and intersected by granitic intrusions. The younger or peninsular gneiss is therefore believed to be a metamorphic series unconformable to the older gneiss. In the western Himalayan chain there are likewise two gneisses—a central gneiss probably Archæan and an upper gneiss formed by the metamorphism of older Palæozoic rocks into which it passes, and which lie unconformably on the older gneiss and contain abundant fragments derived from it.[2]

New Zealand and Australia.—In the South Island of New Zealand the most ancient Palæozoic rocks are underlaid by vast masses of crystalline foliated rocks traceable nearly continuously on the west side of the main watershed. They consist chiefly of varieties of gneiss which are coarse and granitoid in the lower parts. In Canterbury there is a central zone of micaceous, talcose, and graphitic schists overlaid by chlorite- and hornblende-schists, and lastly by a quartzitic zone interleaved with schists.[3] Similar rocks run southward through the west of Otago. The centre of this province is occupied also by a broad band of gently inclined mica-schists. These rocks—the main gold-bearing series of Otago—are believed by Captain Hutton to be not less than 50,000 feet thick, and are referred by him to a later formation than the more crystalline gneiss;[4] but Dr. Haast regards them as only the upper part of the great fundamental granitic gneiss of the island.

In Australia large areas of granite and of crystalline-schists occur, but their precise relations have not yet been worked out. Some of these rocks have been described by Selwyn, Ulrich, and others, as metamorphosed Palæozoic formations. But there are not improbably other areas referable to an Archæan series.

[1] *Amer. Journ. Sci.* xix. (1880), p. 363.

[2] Medlicott and Blanford, "Manual of Geology of India," pp. xviii. xxvi. But there are younger Indian schistose rocks from which these must be distinguished. In the Himalayan region there is a series of gneisses and schists below which lie comparatively unaltered beds of supra-triassic age.

[3] Haast's "Geology of Canterbury," p. 252.

[4] "Geology of Otago," p. 31.

PART II.—PALÆOZOIC.

Under the general term Palæozoic or Primary are now included all the older sedimentary formations containing organic remains, up to the top of the Permian system. These rocks consist mainly of sandy and muddy sediment with occasional intercalated zones of limestone. They everywhere bear witness to comparatively shallow water and the proximity of land. Their frequent alternations of sandstone, shale, conglomerate, and other detrital materials, their abundant rippled and sun-cracked surfaces, marked often with burrows and trails of worms, as well as the prevalent character of their organic remains, show that they must have been deposited in areas of slow subsidence, bordering continental or insular masses of land. As regards the organisms of which they have preserved the casts, the Palæozoic rocks, as far as the present evidence goes, may be grouped into two divisions—an older and a newer:—the former (from the base of the Cambrian to the top of the Silurian system) distinguished more especially by the abundance of its graptolitic, trilobitic, and brachiopodous fauna, and by the absence of vertebrate remains; the latter (from the top of the Silurian to the top of the Permian system) by the number and variety of its fishes and amphibians, the disappearance of graptolites and trilobites, and the abundance of its cryptogamic terrestrial flora.

Section I.—Cambrian.

§ 1.—General Characters.

In those regions of the world where the relations of the Archæan to the oldest Palæozoic rocks are most clearly exposed and have been most carefully studied, a more or less marked unconformability has been observed between the two series. Such a break points no doubt to the lapse of a vast interval of time during which the Archæan formations, after suffering much crumpling and metamorphism, were ridged up into land and were then laid open to prolonged denudation. These changes seem to have been more especially prevalent in the northern part of the northern hemisphere. At all events there is evidence of extensive upheaval of land in the north-west of Europe and across the northern tracts of North America prior to the deposit of the earliest remaining portions of the Palæozoic formations. These strata indeed were derived from the degradation of that northern land, and we may form some idea of its magnitude from the enormous piles of sedimentary rock which have been formed out of its waste. To this day much of the land in the boreal tracts of the northern hemisphere still consists of Archæan gneiss. We cannot affirm that the primeval northern land was lofty; but if it was not, it must have been subjected to repeated renewals of elevation, to compensate for the loss of height which it

suffered in the denudation that provided material for the deep masses of Palæozoic sedimentary rock.

The earliest system or connected suite of deposits in the Palæozoic series has received the name of Cambrian—a term first proposed by Sedgwick for the most ancient sedimentary rocks of North Wales (Cambria).[1] By far the largest mass of these rocks is unfossiliferous, so that their identification in different countries is often entirely arbitrary. The extent and limit of the Cambrian system are probably best seen in the British Islands.

Rocks.—The rocks of the Cambrian series present great uniformity of lithological character over the globe. They consist of grey and reddish grits or greywackes, quartzites, and conglomerates with shales and slates. Their false-bedding, ripple-marks, and sun-cracks indicate deposit in shallow water and occasional exposure of littoral surfaces to desiccation. Sir A. C. Ramsay has suggested that the non-fossiliferous red strata in this system may have been laid down in inland basins, and he has speculated upon the probability even of glacial action in Cambrian time in Britain.[2] As might be expected from their high antiquity and consequent exposure to the terrestrial changes of a long succession of geological periods, Cambrian rocks are usually much disturbed. They have often been thrown into plications, dislocated, placed on end, sometimes cleaved and even metamorphosed.

Life.—Much interest necessarily attaches to the fossils of the Cambrian system, for they are the oldest assemblage of organisms yet known. They form no doubt only a meagre representation of the fauna of which they were once a living part. One of the first reflections which they suggest is that they present far too varied and highly organized a suite of organisms to allow us for a moment to suppose that they indicate the first fauna of our earth's surface. Unquestionably they must have had a long series of ancestors, though of these still earlier forms no trace has yet been recovered, perhaps because the rocks in which any records of them might have been preserved seem to have been everywhere metamorphosed. Thus at the very outset of his study of stratigraphical geology the observer is confronted with a proof of the imperfection of the geological record. When he begins the examination of the Cambrian fauna so far as it has been preserved, he at once encounters further evidence of imperfection. Whole tribes of animals, which almost certainly were represented in Cambrian seas, have entirely disappeared, while those of which remains have been preserved belong to different and widely separated divisions of invertebrate life.[3]

[1] Much controversy has taken place in England in recent years regarding the respective boundaries of the Cambrian and Silurian systems. Into this controversy it is not needful to enter here. The limit which I have taken for the Cambrian rocks is that which appears to me to accord best with palæontological evidence.

[2] *Brit. Assoc.* 1880, Presidential address.

[3] Recently the presence of medusæ in the Cambrian seas has been detected in the casts of their forms found in Sweden by A. G. Nathorst. *Svensk. Akad. Handl.* xix. (1881).

The prevailing absence of limestones from the Cambrian system is accompanied by a failure of the foraminifera, corals, and other calcareous organisms which abound in the limestones of the next great geological series. The character of the general sandy and muddy sediment must have determined the distribution of life on the floor of the Cambrian sea, and doubtless has also affected the extent of the final preservation of organisms actually entombed.

The plants of the Cambrian period have been scarcely at all preserved. That the sea then possessed its sea-weeds can hardly be

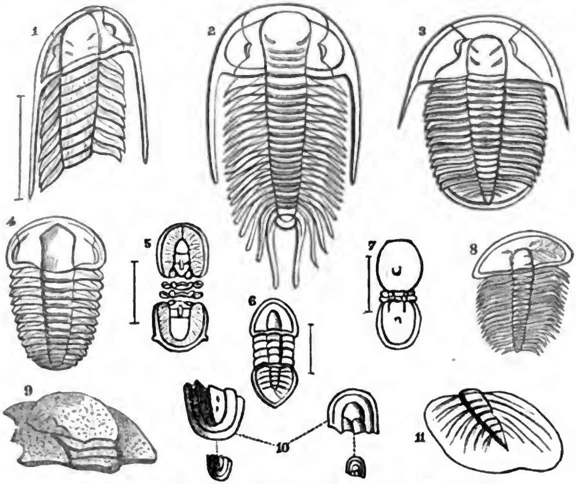

FIG. 319.—GROUP OF CAMBRIAN (PRIMORDIAL) TRILOBITES.[1]

1, Olenus impar (Salt.) (enlarged); 2, Paradoxides Davidis (Salt.) ($\frac{1}{10}$); 3, Conocoryphe (?) Williamsoni (Belt.); 4, Ellipsocephalus Hoffi (Schloth.); 5, Agnostus princeps (Salt.) (enlarged); 6, Microdiscus sculptus (Hicks) (enlarged); 7, Agnostus Barlowii (Belt.) (enlarged); 8, Erinnys venulosa (Salt.); 9, Plutonia Sedgwickii (Salt.); 10, Agnostus cambrensis (Hicks) (and enlarged); 11, Dikelocephalus celticus (Salt.).

doubted, and various fucoid-like markings on slates and sandstones (*e.g.* the "fucoidal sandstone" of Sweden) have been referred to the vegetable kingdom. The genus *Eophyton* from Sweden, and others from the Potsdam sandstone of North America, have been described, but some of these are probably worm-tracks, others are merely imitative wrinkles and markings of inorganic origin, and it is not certain that any of them are truly plants. What has been regarded as an undoubted organism occurs in abundance in the Cambrian

[1] Where not otherwise stated the figures are of the natural size.

rocks of the south-east of Ireland and is named *Oldhamia* (Fig. 320). For many years it was considered to be a sertularian zoophyte, subsequently it was referred to the calcareous algæ; but its true grade seems still uncertain.

Among the animal organisms of the Cambrian rocks the most lowly forms yet detected are hexactinellid sponges (*Protospongia*, Fig. 320), of which four species have been found in Wales. The Echinodermata are represented by crinoids (*Dendrocrinus*), cystideans (*Protocystites*, Fig. 320), and star-fishes (*Palæasterina*, Fig. 321). Annelides existed, as is shown by their trails and burrows (*Arenicolites*, Fig. 320, *Cruziana*). But by far the most abundantly preserved forms of life are crustacea, chiefly belonging to the extinct order of trilobites (Fig. 319). It is a very suggestive fact that these

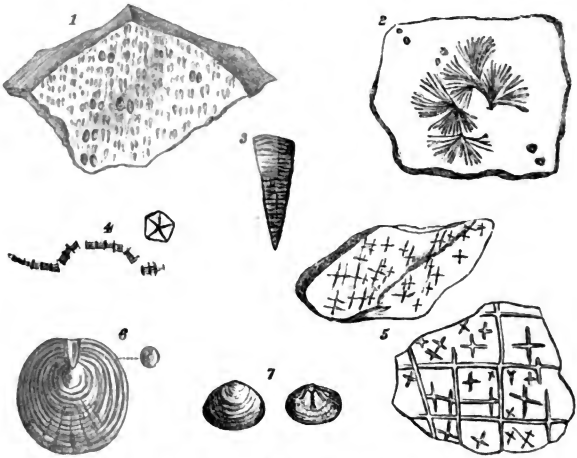

Fig. 320.—Group of Lower Cambrian Fossils.

1, Arenicolites didymus (Salt.); 2, Oldhamia antiqua (Forbes); 3, Theca corrugata (Salt.); 4, Protocystites menevensis (Hicks) ($\frac{1}{1}$); 5, Protospongia fenestrata (Salt.) (and enlarged $\frac{4}{1}$); 6, Discina pileolus (Hicks) (and enlarged); 7, Obolella maculata (Hicks).

organisms appear even here, as it were on the very threshold of authentic biological history, to have reached their full structural development. Some of them indeed were of dimensions scarcely ever afterwards equalled and already presented great variety of form. Individuals of the species *Paradoxides Davidis* are sometimes nearly two feet long. But with these giants were mingled other types of diminutive size. It is noteworthy also, as Dr. Hicks has pointed out, that while the trilobites had attained their maximum size at this early period,

they were represented by genera indicative of almost every stage of development, "from the little *Agnostus* with two rings in the thorax, and *Microdiscus* with four, to *Erinnys* with twenty-four," while blind genera occurred together with those having the largest eyes.[1] Besides those just mentioned, other characteristic genera (Fig. 319) are *Plutonia, Ellipsocephalus, Conocoryphe, Dikelocephalus, Olenus,*

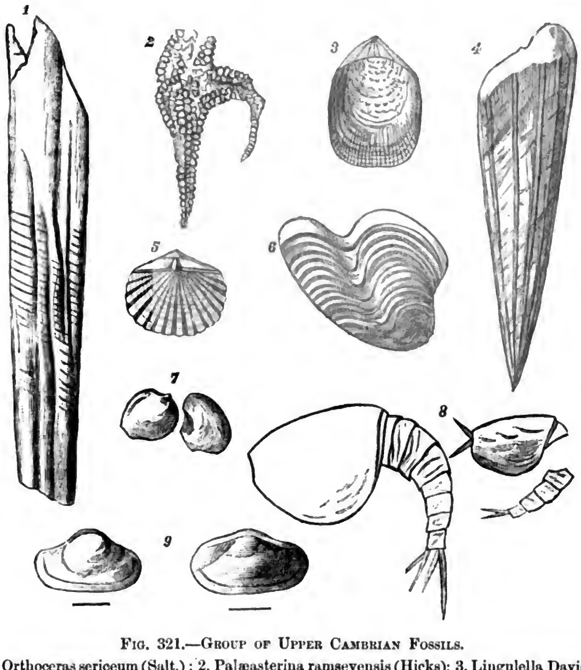

FIG. 321.—GROUP OF UPPER CAMBRIAN FOSSILS.

1, Orthoceras sericeum (Salt.); 2, Palæasterina ramseyensis (Hicks); 3, Lingulella Davisii (McCoy); 4, Conularia Homfrayi (Salt.); 5, Orthis Carausii (Salt.); 6, Bellerophon arfonensis (Salt.); 7, Palæarca Hopkinsoni (Hicks); 8, Hymenocaris vermicauda (Salt.) (and enlarged); 9, Ctenodonta cambrensis (Hicks) (enlarged).

and *Anopolenus*. Phyllopod crustaceans likewise occur; the most characteristic genus being *Hymenocaris* (Fig. 321).

In striking contrast to the thoroughly Palæozoic and long extinct order of trilobites, the brachiopods appear in genera some of which are still familiar in the living world. *Lingula* and *Discina* (Fig. 320),

[1] *Q. J. Geol. Soc.* xxviii. p. 174.

which appear among these ancient rocks, have persisted with but little change, at least in external form, through the whole of geological time and are alive still. Other genera are *Lingulella* (Fig. 321), *Obolella* (Fig. 320), *Kutorgina*, and *Orthis* (Fig. 321). Every class of the true mollusca had its representatives in the Cambrian seas. The lamellibranchs occurred in the genera *Ctenodonta* (Fig. 321), *Palæarca, Davidia*, and *Modiolopsis*. The gasteropods were present in the heteropod genus so characteristic of Palæozoic time, *Bellerophon* (Fig. 321). The pteropods were represented by the genera *Theca* (Fig. 320) and *Conularia*, the cephalopods by *Orthoceras* (Fig. 321).

Taking palæontological characters as a guide in classification it has been proposed to group the Cambrian system according to the distribution of characteristic trilobites, into two divisions—the lower (Harlech or Longmynd and Menevian rocks of Britain) termed Paradoxidian, and the upper (Lingula and Tremadoc) Olenidian.

§ 2. Local Development.

Britain.[1]—The area in which the fullest development of the oldest known Palæozoic rocks has yet been found is undoubtedly the principality of Wales. The rocks are there much thicker than in any other known region, they have yielded a more abundant fauna, and they possess additional importance from the fact that they were the first strata of such antiquity to be worked out stratigraphically and palæontologically. As already stated, they were named Cambrian by Sedgwick, from their extensive development in Cambria or North Wales, where he originally studied them. Their true base is nowhere seen. According to Sedgwick and subsequent observers (especially Messrs. Hicks, Hughes, and Bonney) they rest unconformably upon a set of igneous and metamorphic Archæan rocks, so that their base at any given locality must be merely a local phenomenon. Professor Hughes believes that a strong conglomerate and grit generally mark the base of the Cambrian series.[2] According to Professor Ramsay on the other hand, the base of the Cambrian series is either concealed by overlying formations or by the metamorphism which he thinks has converted portions of the Cambrian series into various crystalline rocks. Starting from the lowest observable horizon among these ancient sedimentary deposits, the geologist can trace an upward succession through many thousands of feet of grits and slates into the Silurian system. Considerable diversity of opinion has existed, and still continues, as to the line where the upper limit of the Cambrian system should be drawn. Murchison contended that this line should be placed below strata where a trilobitic and brachiopodous fauna begins, and that these strata cannot be separated from the overlying Silurian

[1] See Sedgwick's Memoirs in *Quart. Journ. Geol. Soc.*, vols. i. ii. iv. viii., and his "Synopsis of the Classification of the British Palæozoic Rocks," 4to, 1855; Murchison's "Siluria," and Ramsay's "North Wales," in *Geological Survey Memoirs*, vol. iii., and papers by Salter, Harkness, Hicks, Hughes, and others in the *Quart. Journ. Geol. Soc.* and *Geol. Mag.*, to some of which reference is made below.

[2] *Q. J. Geol. Soc.* xxxiv. p. 144.

system. He therefore included as Cambrian only the barren grits and slates of the Longmynd, Harlech, and Llanberis. Sedgwick, on the other hand, insisted on carrying the line up to the base of the Upper Silurian rocks. He thus left these rocks as alone constituting the Silurian system, and massed all the Lower Silurian in his Cambrian system. Murchison worked out the stratigraphical order of succession from above, and chiefly by help of organic remains. He advanced fron. where the superposition of the rocks is clear and undoubted, and for the first time in the history of geology ascertained that the "transition-rocks" of the older geologists could be arranged into zones by means of characteristic fossils as satisfactorily as the Secondary formations had been classified in a similar manner by William Smith. Year by year, as he found his Silurian types of life descend farther and farther into lower deposits, he pushed backward the limits of his Silurian system. In this he was supported by the general consent of geologists and palæontologists all over the world. Sedgwick, on the other hand, attacked the problem rather from the point of stratigraphy and geological structure. Though he had collected fossils from many of the rocks of which he had made out the true order of succession in North Wales, he allowed them to lie for years unexamined. Meanwhile Murchison had studied the prolongations of some of the same rocks into South Wales, and had obtained from them the copious suite of organic remains which characterized his Lower Silurian formations. Similar fossils were found abundantly on the continent of Europe and in America. Naturally the classification proposed by Murchison was generally adopted. As he included in his Silurian system the oldest rocks containing a distinctive fauna of trilobites and brachiopods, the earliest fossiliferous rocks were everywhere classed as Silurian. The name Cambrian was regarded by geologists of other countries as the designation of a British series of more ancient deposits not characterized by peculiar organic remains, and therefore not capable of being elsewhere satisfactorily recognized. Barrande, investigating the most ancient fossiliferous rocks of Bohemia, distinguished by the name of the "Primordial Zone" a group of strata underlying the Lower Silurian rocks, and containing a peculiar and characteristic suite of trilobites. He classed it, however, with the Silurian system, and Murchison adopted the term, grouping under it the lowest dark slates which in Wales and the border English counties contained some of the same early forms of life.

More recent investigations, however, first by the late Mr. Salter and Dr. Hicks, and subsequently by the latter observer, brought to light, from the so-called primordial rocks of Wales, a much more numerous fauna than they were supposed to possess, and one in large measure distinct from that in the undoubted Lower Silurian rocks. Thus the question of the proper base of the Silurian system was re-opened, and the claims of the Cambrian system to a great upward extension were more forcibly urged than ever. But these claims could now be based on palæontological evidence such as had never before been produced. Accordingly there has arisen a general desire among the geologists of Britain to revise the nomenclature of the older rocks. Though as yet a common accord of opinion has not been reached, there seems a strong probability that ultimately the boundary line between the Cambrian and Silurian systems will be drawn above the primordial zone along the

base of the great Arenig group or Lower Llandeilo rocks of Murchison. All his Silurian strata of older date than these rocks will be classed as Cambrian. It is undoubtedly true, however, that although a decided break occurs in the succession of species at the top of the Cambrian series, the general palæontological resemblance of the Cambrian and Silurian systems as thus discriminated is singularly close; so close indeed, that there may not improbably be a subsequent revision of this question with the result of throwing all these older Palæozoic rocks into one palæontological system.

According to the classification here adopted, the Cambrian system, as developed in North Wales and the border English counties, consists of purple, reddish-grey, and green slates, grits, sandstones, and conglomerates, which are estimated to reach the enormous thickness of 25,000 feet. By far the larger part of this vast depth of rock is unfossiliferous. Indeed it is only in some bands of the upper 6000 feet, or thereabouts, that fossils occur plentifully. The total British Cambrian fauna discovered up to the present time embraces 61 genera and 182 species. By fossil evidence the Cambrian system may be divided into Lower and Upper, and each of these sections may be further subdivided into two groups, as in the following table:

Cambrian of Wales.	Upper.	4. Tremadoc slates.
		3. Lingula flags.
	Lower.	2. Menevian group.
		1. Harlech and Longmynd group.

1. *Harlech and Longmynd Group.*—This group consists of purple, red, and grey flags, sandstones, and slates, with conglomerates. These strata attain a great thickness, estimated at 4000 feet in South Wales, more than 8000 in North Wales, and perhaps 25,000 in Shropshire. They were formerly supposed to be nearly barren of organic remains; but in recent years, chiefly through the researches of Dr. Hicks at St. David's, they have yielded a tolerably abundant fauna, consisting of 32 species. Among these are 7 genera and 14 species of trilobites (*Paradoxides*, *Plutonia*, *Microdiscus*, *Palæopyge*, *Agnostus*, *Conocoryphe*), four annelides (*Arenicolites*), a sponge (*Protospongia*), six brachiopods (*Discina*, *Lingulella*), two pteropods (*Theca*), &c. Many of the surfaces of the strata in some parts of this group are marked with ripples, sun-cracks, and rain-pittings, as well as with trails of worms—indicative of shallow-water and shore-conditions of deposit. Twelve of the 32 species, according to Mr. Etheridge, pass up into the Menevian group.[1]

2. *Menevian Group.*—This subdivision has been proposed for a series of sandstones and shales, with dark-blue slates, flags, and grey grits, which are seen near St. David's (Menevia), where they attain a depth of about 600 feet. They pass down conformably into the Harlech group, with which, as just stated, they are connected by 12 species in common. The Menevian beds have yielded 52 species of fossils, of which 19 pass up into the lower Lingula flags. Among them the trilobites are specially prominent, 12 genera and 32 species having been obtained from the Menevian beds, among which the genera *Agnostus* (7 species), *Conocoryphe* (7 species), and *Paradoxides* (3 species) are specially characteristic. Four species of sponges (*Protospongia*), three of which are

[1] *Q. J. Geol. Soc.* xxxvii. (1881), President's address, p. 41.

found in the Longmynd group, and some annelide-tracks likewise occur. The mollusca are represented by six species of brachiopods of the genera *Discina*, *Lingulella*, *Obolella*, and *Orthis;* 6 pteropods (*Cyrtotheca*, *Theca*) have been met with. The earliest entomostracan (*Entomis*) and cystidean (*Protocystites*) yet discovered occur in the Menevian fauna.

3. *Lingula Flags.*—These strata, consisting of bluish and black slates and flags, with bands of grey flags and sandstones, attain in some parts of Wales a thickness of more than 5000 feet. They received their name from the discovery by Mr. E. Davis (1846) of vast numbers of a *Lingula* (*Lingulella Davisii*) in some of their layers. They rest conformably upon, and pass down into, the Menevian beds below them, and likewise graduate into the Tremadoc group above. They are distinguished by a characteristic suite (71 species) of organic remains. The trilobites include the genera *Agnostus*, *Anopolenus*, *Conocoryphe*, *Dikelocephalus*, *Erinnys*, *Olenus*, and *Paradoxides*. The earliest phyllopods (*Hymenocaris*) and heteropods (*Bellerophon*) occur in these beds. The brachiopods include species of *Lingulella* (*L. Davisii*), *Discina*, *Obolella*, and *Orthis*. The pteropods are represented by three species of *Theca*. Several annelides (*Cruziana*) and polyzoa (*Fenestella*) likewise occur.

According to Mr. Etheridge, the Lingula flags may be grouped into three zones, each characterized by a peculiar assemblage of organic remains. The lower division contains 36 species, of which seven are peculiar to it. The middle zone, which is of quite subordinate value, has yielded five species, two of which (*Conocoryphe bucephala* and *Lingulella Davisii*) pass down into the lower division, one (*Kutorgina cingulata*) ascends into the upper, and two (*Lingula squamosa* and *Bellerophon cambrensis*) are peculiar. The upper zone has yielded 41 species. Of these ten pass up into the Tremadoc beds, while two (*Lingulella lepis* and *L. Davisii*) continue on into the Arenig group.[1]

4. *Tremadoc Slates.*—This name was given by Sedgwick to a group of dark grey slates, about 1000 feet thick, found near Tremadoc in Carnarvonshire, and traceable thence to Dolgelly. Their importance as a geological formation was not recognized until the discovery in them of a remarkably abundant and varied fauna which now numbers 84 species. They contain the earliest crinoids, star-fishes, lamellibranchs, and cephalopods yet found. The trilobites embrace some genera (*Agnostus*, *Conocoryphe*, *Olenus*, &c.) found in the Lingula flags, but include also the new forms, *Angelina*, *Asaphus*, *Cheirurus*, *Neseuretus*, *Niobe*, *Ogygia*, *Psilocephalus*, &c. The same genera, and in some cases species, of brachiopods appear which occur in the Lingula flags, *Orthis Carausii* and *Lingulella Davisii* being common forms. Dr. Hicks has described 12 species of lamellibranchs from the Tremadoc beds of Ramsay Island and St. David's, belonging to the genera *Ctenodonta*, *Palæarca*, *Glyptarca*, *Davidia*, and *Modiolopsis*. The cephalopods are represented by *Orthoceras sericeum* and *Cyrtoceras præcox;* the pteropods by *Theca Davidii*, *T. operculata*, and *Conularia Homfrayi;* the echinoderms by a beautiful star-fish (*Palæasterina ramseyensis*) and by a crinoid (*Dendrocrinus cambrensis*).[2]

Careful analysis of the fossils yielded by the Tremadoc beds suggests a division of this group into two zones. According to Mr. Etheridge, the Lower Tremadoc rocks have yielded in all 28 genera and 58 species,

[1] Etheridge, *Q. J. Geol. Soc.* 1881. President's address, p. 48.
[2] Hicks, *Quart. Journ. Geol. Soc.* xxix. p. 39.

of which 8 genera and 9 species pass down into the Lingula flags and 9 genera and 13 species ascend into the Upper Tremadoc zone. The most characteristic forms are *Niobe Homfrayi*, *N. menapiensis*, *Psilocephalus innotatus*, *Angelina Sedgwickii*, *Asaphus affinis*. The Upper Tremadoc beds contain, as at present ascertained, 20 genera and 33 species, of which only 16 species pass up into the Arenig group. It is at the top of the Upper Tremadoc strata that the line between the Cambrian and Silurian systems is here drawn. According to Sir A. C. Ramsay, there is evidence of a physical break at the top of the Tremadoc beds of Wales, so that on a large scale the next succeeding or Arenig strata repose unconformably upon everything older than themselves; while Mr. Etheridge remarks that no greater break in palæontological succession occurs in the whole series of Palæozoic rocks than at this point, for besides the small percentage of fossils of the one series that passes over into the other (16 species in all) the character of the Arenig fauna strongly distinguishes it from that of the formations below, and further supports the line of division here adopted between the Cambrian and Silurian rocks. But, as already remarked, the demarcation does not interfere with the broad general resemblance in the palæontological facies of the two systems. Unfortunately in England, where the question has been principally discussed, personal considerations have been allowed to influence the judgment, the partizans of Sedgwick on the one hand and of Murchison on the other contending for the claims of the rival geological chiefs. When the personal element can be entirely eliminated, and the question is discussed on its own merits, the line of demarcation between Cambrian and Silurian, as above suggested, will not improbably be effaced, and the whole will be regarded as one great palæontological system.

In the north-west of Scotland a mass of reddish-brown and chocolate-coloured sandstone and conglomerate (at least 8000 feet thick in the Loch Torridon district) lies unconformably upon the Archæan gneiss in nearly horizontal or gently inclined beds. It rises into picturesque groups of mountains, which stand out as striking monuments of denudation, seeing that the truncated ends of their component flat strata can be traced even from a distance forming parallel bars along the slopes and precipices. The denudation must have been considerable even in early Silurian times, for the sandstones are unconformably overlaid by quartz-rocks and limestones containing Lower Silurian fossils, and these younger strata even in the same district rest directly on the Archæan gneiss. Here and there at the base of the red sandstone lies a remarkably coarse breccia containing huge angular blocks of gneiss. At these localities rounded dome-like bosses of gneiss pass under the breccia and forcibly recall the *roches moutonnées* of more recent times.[1] No trace of organic remains of any kind has been found in the red sandstones themselves, unless certain track-like impressions, observed on the west side of Loch Maree, can be regarded as having been imprinted by crustacea or other organisms.[2] These sandstones were at one time regarded as Old Red Sandstone, though Macculloch, and afterwards Hay Cunningham, pointed out that they underlie parts of the schistose rocks of the northern Highlands. The discovery by Mr. C. W. Peach of Lower Silurian shells in the overlying limestones showed that the massive red

[1] *Nature*, August (1880) xxii. p. 400.

[2] *Nature*, xxiii. p. 93.

sandstones of western Ross and Sutherland could not be paralleled with those of the eastern tracts of those counties, but must be of older date than part of the Llandeilo rocks of the Lower Silurian period. Sir R. Murchison classed them as Cambrian—an identification which finds support in the lithological resemblance between these rocks of the north-west Highlands and much of the Lower Cambrian system of Wales.

In the south-east of Ireland masses of purplish, red, and green shales, slates, grits, quartz-rocks, and schists occupy a considerable area and attain a depth of 14,000 feet without revealing their base, while their top is covered by unconformable formations (Lower Silurian and Lower Carboniferous). They have yielded *Oldhamia*, also numerous burrows and trails of annelides (*Histioderma Hibernicum*, *Arenicolites didymus*, *A. sparsus*, *Haughtonia pœcila*). No Upper Cambrian forms have been met with in these Irish rocks, which are therefore placed with the Lower Cambrian, the unconformability at their top being regarded as equivalent to the interval required for the deposition of the intervening formations up to the time of the Llandeilo rocks, as in the north-west of Scotland. Some portions of the Irish Cambrian series have been intensely metamorphosed. Thus on the Howth coast they appear as schists and quartz-rocks; in Wexford they pass into gneiss and granite. In West Galway a vast mass of schists, quartz-rocks, and limestones (8000 feet and upwards) passes up into schistose and hornblendic, as well as unaltered rocks containing Llandeilo fossils. These have been supposed by Mr. Kinahan to be probably Cambrian. He suggests that they are Upper Cambrian, which would imply that Upper Cambrian rocks pass conformably into the Llandeilo formation without the occurrence of the thick Arenig rocks of Wales. In a difficult country, however, broken by faults and greatly metamorphosed, an unconformability might easily escape detection. According to Mr. Hull, the Galway and Mayo rocks contain no representatives of the Cambrian system. In his view the oldest portions (hornblende-schist, gneiss, &c.) are Archæan, covered (unconformably, no doubt) by generally metamorphosed Lower Silurian rocks, above which come Upper Silurian non-metamorphosed strata.

Continental Europe.—According to the classification adopted by M. Barrande, the fauna of the older Palæozoic rocks of Europe suggests an early division of the area of this continent into two regions or provinces,—a northern province, embracing the British Islands, and extending through North Germany into Scandinavia, on the one hand, and into Russia on the other, and a central-European province, including Bohemia, France, Spain, Portugal, and Sardinia.

Passing from the British type of the Cambrian deposits we encounter nowhere in the northern part of the continent so vast a depth of stratified deposits. In central and northern Norway the Archæan gneiss is overlaid by reddish and grey sandstones and conglomerates (Sparagmite), with schists, quartzites, and limestones. Above these rocks, which, according to Kjerulf, are partly coeval with the Archæan series, lies the "Primordial Zone" (p. 659). Near Kongsberg it is made up of a lower band (8 feet) of conglomerate, sandstone, and schist, followed by 60 feet of black shales with *Paradoxides Tessini*, *P. rugulosus*, *Agnostus fallax*, *A. parvifrons*, *A. gibbus*, *A. incertus*, above which come more dark shales (22 feet) with *Paradoxides Forchhammeri*, *Agnostus Kjerulfi*, *A. brevifrons*, *A. aculeatus*, *Protospongia*, &c. In the Christiania district there occur (1) a lower zone 90 Norwegian feet thick, composed of con-

glomerates, sandstones, and dark shales with limestone, and containing *Paradoxides Tessini* and *P. Forchhammeri;* and (2) an upper zone (150 feet) composed of black slates (Alum slates) and fetid limestone, with *Olenus*, &c. In Sweden the Cambrian series comprises (1) "Eophyton and Fucoid Sandstones"—sandstones and green shales with *Eophyton*, *Palæophycus*, and numerous other somewhat obscure impressions (*Regio fucoidarum* of Angelin), and the first traces of the primordial fauna (*Theca*, *Obolus*, &c.); thickness from not more than 50 or 60 to 400 feet. (2) "Paradoxides Beds"—black alum slates, with an intercalated band of limestones (Andrarumskalk); united thickness only a few feet. According to Linnarsson the group may be subdivided into six zones, each marked by its characteristic trilobite, viz., 1. *Paradoxides Kjerulfi; 2. P. Tessini; 3. P. Davidis; 4. P. Oelandicus; 5. P. Forchhammeri* (= Andrarum limestone); 6. *Agnostus lævigatus.* The same author gives a census of the fauna of these beds, from which it appears that they contain 44 species of trilobites—1 *Leperditia*, 3 pteropods (*Theca*), 11 brachiopods, and a sponge. (3) "Olenus schists" comprising the upper part of the black alum slates containing *Olenus*, thickness not more than 40 or 50 feet, yet believed by Linnarsson to contain palæontological equivalents for every horizon of the thick English Lingula flags. (4) "Dictyonema schists," full of *Dictyonema flabelliforme* with a *Dichograptus* and *Obolella*. A remarkable group of primordial trilobites has recently been obtained from a limestone (*Exulans* zone) lying probably about the horizon of the *Tessini* zone in Scania. The forms are for the most part peculiar to Scandinavia, and include species of the genera *Paradoxides*, *Conocoryphe*, *Liostracus*, *Solenopleura*, *Agnostus*, *Hyolithus* (*Theca*), *Lingulella*, and *Obolella*.[1]

It is uncertain whether the Scandinavian Cambrian series should be regarded as representing the whole of the enormously thicker British system or only the upper part of it. On the former supposition we must conceive that while the British area underwent a subsidence of more than 20,000 feet the Scandinavian region did not sink more than about a hundredth part of that amount. The Cambrian formations appear to thin out eastwards from Sweden, for they have not yet been satisfactorily recognized among the undisturbed Palæozoic sediments of north-western Russia.

In Central Europe Cambrian rocks appear from under later accumulations in Belgium and the north of France, Spain, Bohemia, and the Thuringer Wald. The most important in France and Belgium is that of the Ardennes, where the principal rocks are grit, sandstone, slates, and schistose quartzites or quartz-schists (quartzophyllades of Dumont), with bands of whet-slate, quartz-porphyry, diabase, diorite, and porphyroid. According to Dumont these rocks, comprehended in his "Terrain Ardennais," can be grouped into three great subdivisions—1st, the "Système Devillien," pale and greenish quartzites with slates or phyllades, containing *Oldhamia radiata* and annelide tubes; 2nd, the "Système Revinien," phyllades and black pyritous quartzites from which *Dictyonema sociale*, *Eophyton Linnæanum*, and worm-burrows have been obtained; 3rd, the "Système Salmien"

[1] Kjerulf, "Geologie des Südl. und Mittl. Norwegen," 1880. W. Brögger, *Nyt. Mag.* 1876. *Geol. Foren. Forhandl.* 1875–76. Angelin, "Palæontologia Suecica," 1851–54. Dahll, "Vidensk-Selsk. Forhandl." 1867. Linnarsson, "Svensk. Vet. Akad. Handl." 1876, iii. No. 12; *Geol. Mag.* vi. (1869), p. 393; iii. 2nd Dec. 1876, p. 145. "Om Faunen in Kalken med *Conocoryphe exulans*," Stockholm, 1879. Lundgren, in text to Angelin's Geol. Map of Scania, *N. Jahrb.* 1878. Lapworth, *Geol. Mag.* 1881, p. 260.

consisting mainly of quartzose and schistose strata or quartzo-phyllades, and yielding remains of *Paradoxides* and *Lingula*. All these rocks have been greatly disturbed and are covered unconformably by Devonian and later formations.[1] In the north-west of France a large tract of Palæozoic rocks spreads through Brittany and the west of Normandy. Recent researches have shown that in that region there is an old gneiss with overlying mica-schists followed by a mass of what used to be called "transition" strata, which appear to contain representatives of Cambrian, Silurian, and Devonian deposits. Towards the west of this region the gneiss and mica-schist are succeeded by green silky talcose-schists (phyllades de Douarnenez) and then by 100 to 120 metres of conglomerate and red shale. These strata may be Cambrian. They are followed by a persistent group of white sandstone and shale with *Scolithus linearis* (*Grès armoricain*),[2] which may be the basement zone of the Silurian system of the north-west of France. In the basin of Rennes considerable bands of limestone, sometimes magnesian, together with quartzites, conglomerates, and greywackes occur in the great series of Cambrian schists. Traces of annelides and perhaps of *Oldhamia* occur in these strata, but no evidence of the true primordial zone with its characteristic trilobite fauna has yet been discovered.[3]

The classic researches of M. Barrande have given to the oldest fossiliferous rocks of Bohemia an extraordinary interest. He has made known the existence there of a remarkable suite of organic remains representative of those which characterize the Cambrian rocks of Britain. At the base of the geological formations of that region lie the Archæan gneisses already mentioned. These are overlaid by vast masses of schists, conglomerates, quartzites, slates, and igneous rocks, which have been more or less metamorphosed, and are singularly barren of organic remains, though some of them have yielded traces of annelides. They pass up into certain grey and green fissile shales, in which the earliest well-marked fossils occur. The organic contents of this Étage C or Primordial zone form what M. Barrande terms his primordial fauna, which contains 40 or more species, of which 27 are trilobites, belonging to the characteristic Cambrian genera—*Paradoxides* (12), *Agnostus* (5), *Conocoryphe* (4), *Ellipsocephalus* (2), *Hydrocephalus* (2), *Arionellus* (1), *Sao* (1). Not a single species of any one of these genera, save *Agnostus* (of which four species appear in the second fauna), has been found by M. Barrande higher than his primordial zone. Among other organisms in this primordial fauna, the brachiopods are represented by two species (*Orthis* and *Orbicula*), the pteropods by five (*Theca*), and the echinoderms by five cystideans.

North America.—Rocks corresponding in position and in the general character of their organic contents with the Cambrian formations of Europe have been recognized in different parts of the United States and Canada. They appear in Newfoundland, whence, ranging by Nova Scotia and New Brunswick, they enter Canada, the northern parts of New York, Vermont, and eastern Massachusetts. They rise again along the Appalachian ridge, in Wisconsin, Minnesota, Missouri, Arkansas,

[1] Dewalque, "Prodrome d'une Description Géol. de la Belgique," 1868. Mourlon, "Géologie de la Belgique," 1880. Gosselet, "Esquisse Géol. du Nord de la France, &c.," 1880.

[2] Barrois, *Bull. Soc. Géol. France*, v. (1877), p. 266.

[3] Tromelin et Lebesconte, *Bull. Soc. Géol. France*, iv. (1876), p. 583. Barrois, *Op. cit.* v. (1877), p. 267.

Texas, and Georgia. Westwards from the great valley of the Mississippi, where they have been found in many places, they reappear from under the Mesozoic and younger Palæozoic rocks of the Rocky Mountains. They have been divided by American geologists into two formations—(1) Acadian, a mass (2000 feet) of grey and dark shales and some sandstones; and (2) Potsdam (or Georgian), which attains in Newfoundland a depth of 5600 feet, but thins away westward and southward till in the valley of the St. Lawrence, where it was studied by Logan and his associates of the Geological Survey of Canada, it is only from 300 to 600 feet thick.

Among the organic remains of the North American Cambrian rocks fucoid casts appear in many of the sandstones, but no traces of higher vegetation. The Acadian formation has yielded primordial trilobites of the genera *Paradoxides*, *Conocoryphe*, *Agnostus*, and some others; brachiopods of the genera *Lingulella*, *Discina*, *Obolella*, and *Orthis;* and several kinds of annelide-tracks. The Potsdam rocks contain a few sponges, the earliest forms of graptolite, some brachiopods, including, besides the genera in the Acadian beds, *Obolus*, *Camarella*, and *Orthisina;* some pteropods (*Hyolithus* or *Theca*); two species of *Orthoceras;* annelide-tracks; trilobites of the genera *Conocoryphe*, *Agnostus*, *Dikelocephalus*, *Olenellus*, *Ptychaspis*, *Chariocephalus*, *Aglaspis*, and *Illænurus*. Some of these genera ascend into the base of the Silurian system, but *Aglaspis*, *Chariocephalus*, *Illænurus*, *Olenellus*, *Paradoxides*, *Phemphigaspis*, and *Triarthrella* are confined to the Cambrian zones.

M. Barrande has called attention to the remarkable uniformity of character in the organic remains of his primordial zone over the continents of Europe and America. He published eleven years ago the subjoined table, to show how close is the parallelism between the proportions in which the different classes of the animal kingdom are represented.[1]

Countries.	Crustaceans.				Molluscs.				Inferior Classes.			Total by Countries.
	Trilobites.	Other Crustacea.	Ostracods.	Annelides.	Pteropods.	Heteropods.	Gasteropods.	Brachiopods.	Bryozoans.	Cystideans.	Sponges.	
1. Bohemia	27	..	..	..	5	..	..	2	1	5	..	40
2. Spain	9	..	1	..	..	..	2	6	..	1	..	19
3. Scandinavia { Regiones A and B }	77	..	5	..	2	..	..	8	4	..	..	96
4. England { Menevian Harlech, part }	33	1	4	4	7	..	..	6	..	1	2	58
5. Newfoundland	2	..	..	..	..	..	..	..	..	..	..	2
6. New Brunswick	18	..	..	..	..	..	..	6	..	1	..	25
7. New York	5	..	..	..	..	..	..	..	..	..	..	5
8. Braintree (Massachusetts)	1	..	..	..	..	..	..	..	..	..	..	1
	172	1	10	4	14	..	2	28	5	8	2	=246

[1] *Trilobites*, Prague, 1871, p. 193. Since the publication of this table the progress of research has increased the number of species from most localities; but the general facies of the primordial fauna has not been materially affected thereby.

Section II. Silurian.

The important system of rocks next to be described was first investigated by the late Sir R. I. Murchison in Wales and the bordering counties of England. He found it to be characteristically developed over the tract once inhabited by the Silures, an ancient British tribe, and he thence chose the name of Silurian as a convenient designation. Passing down conformably into the Tremadoc slates at the top of the Cambrian series, and being covered conformably by the base of the Old Red Sandstone, it there represents a somewhat better defined section of Palæozoic time than the Cambrian system, and offers a more satisfactory base for comparison in other countries. No geological suite of deposits has been traced over a wider extent of the earth's surface, or presents, on the whole, so uniform a series of lithological and palæontological characters.

§ 1.—General Characters.

ROCKS.—The Silurian system consists usually of a massive series of greywackes, sandstones, grits, shales, or slates, with occasional bands of limestone. The arenaceous strata include pebbly grits and conglomerates, which are specially apt to occur at or near any local base of the formation, where they rest unconformably on older rocks. Occasional zones of massive conglomerate occur, as among the Llandovery rocks of Britain. The argillaceous strata are in some regions (Livonia, &c.) mere soft clays: most commonly they are hard fissile shales, but in some regions, (Wales, &c)., where they have been subjected to intense compression, they appear as hard cleaved slates or even as schist and gneiss (Scotland, Ireland). In Europe the limestones are, as a rule, lenticular, as in the examples of the Bala, Aymestry, and Dudley bands, though in the basin of the Baltic some of the limestones have a greater continuity. In North America, on the other hand, the Trenton limestone in the Lower, and the Niagara limestone in the Upper Silurian system are among the most persistent formations of the United States. Easily recognizable bands in many Silurian tracts, especially in the north-west of Europe, are certain dark anthracitic shales or schists, which, though sometimes only a few feet thick, can be followed for many leagues. As they usually contain much decomposing iron disulphide which produces an efflorescence of alum, they are known in Scandinavia as the alum-schists. In Scotland they are the chief repositories of the Lower Silurian graptolites. Their black, coal-like aspect has led to much fruitless mining in them for coal. In the northern part of the State of New York, a series of beds of red marl with salt and gypsum occurs in the Upper Silurian series, and in the Salt Range of the Punjaub a group of saliferous strata belongs to a still older period. These salt-bearing

deposits are the oldest yet discovered. In Styria and Bohemia important beds of oolitic hæmatite and siderite are interstratified with the ordinary greywackes and shales. Occasionally sheets of various eruptive rocks (felsites, diabases, diorites, &c.) occur contemporaneously imbedded in the Silurian rocks (N. Wales, &c.), and with their associated tuffs represent the volcanic ejections of the time.

As a rule Silurian rocks have suffered from subsequent geological revolutions, so that they now appear inclined, folded, contorted, broken, and cleaved, sometimes even metamorphosed into crystalline schists. In certain regions, however (Basin of the Baltic, New York, &c.), they still remain nearly in their original undisturbed positions.

Life.—The general aspect of the life of the Silurian period so far as it has been preserved to us, may be gathered from the following summary published by Dr. Bigsby in 1868—plants 82 species; amorphozoa 136; foraminifera 25; cœlenterata 507; echinodermata 500; annelida 154; cirripedes 8; trilobita 1611; entomostraca 318; polyzoa 441; brachiopoda 1650, monomyaria 168; dimyaria 541; heteropoda 358; gasteropoda 895; cephalopoda 1454; pisces 37; class uncertain 12; total 8897 species. M. Barrande in 1872 published another census in which some variations are made in the proportions of this table, the total number of species being raised to 10,074.

The plants as yet recovered are chiefly fucoids. In many cases they occur as mere impressions which may sometimes be not of vegetable origin at all, but casts of the trails or burrows of worms, &c. Among the most abundant genera are *Buthotrephis, Arthrophycus, Palæophycus,* and *Nematophycus* (Carruth.), the latter having apparently been a gigantic form somewhat like the living arborescent *Lessonia.* But in the Upper Silurian rocks beautifully preserved sea-weeds like the living *Gelidium* or *Plocamium* occur, such as the *Chondrites verisimilis* (Salt.) of the Ludlow rocks of Edinburghshire. Traces, however, of a higher vegetation have been discovered which are of special interest as being the earliest known remains of a land flora. Many years ago certain minute bodies found in the Ludlow bone-bed were regarded as lycopodiaceous spore-cases, but some doubt has been cast on their organic grade. More recently, however, Dr. Hicks has obtained from the Denbighshire grits of N. Wales other spores probably lycopodiaceous.[1] True lycopods (*Sagenaria*) have been met with in the Upper Silurian rocks of Bohemia and a supposed fern (*Eopteris Andegaveris*) in the Lower Silurian slaty schists of Angers containing *Calymene Tristani.*[2] From the Clinton limestone of Ohio portion of a lepidodendroid tree (*Glyptodendron Eatonense*) has been obtained. The Cincinnati group of strata has also yielded a *Sphenophyllum.* From the meagre evidence as yet collected, it would appear that the land of the

[1] *Q. J. Geol. Soc.* 1881, p. 482.

[2] G. De Saporta, *Comptes rendus,* lxxxv. (1877), No. 10. M. Meunier-Chalmas has suggested that this supposed fern is a crystallization of pyrites—a view taken also by Mr. Carruthers.

Silurian period had a cryptogamic vegetation in which lycopods and ferns no doubt played the chief part.

In the **fauna** of the Silurian rocks the most lowly organisms known are foraminifera, of which several genera, including the still living genus *Saccammina*, have been detected. Among these forms may perhaps be included, the singular fossils described as *Ischadites*, *Receptaculites*, and *Nidulites*, of which the true relations are not yet well understood. The Silurian seas possessed representatives of the calcareous and of the siliceous sponges of modern times. Under the former group may be placed the genus *Archæocyathus* of the Lower, and the genera *Astræospongia* and *Amphispongia* of the Upper Silurian rocks; under the latter group come *Astylospongia* and *Protachilleum*. With these fossils may be placed the abundant and still doubtful form *Stromatopora*.

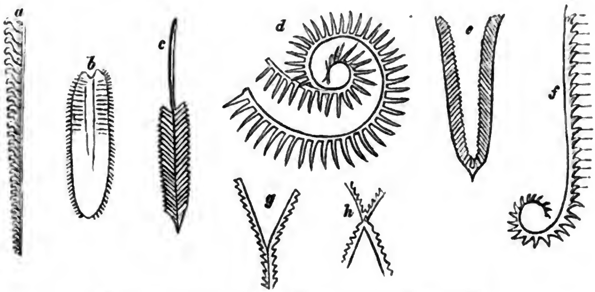

FIG. 322.—GROUP OF LOWER SILURIAN GRAPTOLITES.

a, Monograptus (Graptolithus) priodon (Bronn); *b*, Phyllograptus typus (Hall); *c*, Diplograptus folium (His.); *d*, Rastrites peregrinus (Barr); *e*, Didymograptus Murchisonii (Beck); *f*, Monograptus (Graptolithus) Sedgwickii (Portl.); *g*, Dicranograptus ramosus (Hall); *h*, Tetragraptus Hicksii (Hopk.).

Some of the most plentiful and characteristic denizens of the Silurian seas were undoubtedly the various hydrozoan genera united under the common name of graptolites (Fig. 322). Among the monoprionidian forms, or those with a single row of cells, the genera *Rastrites* and *Monograptus* (*Graptolithus*) are abundant. The diprionidian forms, or those with two rows of cells, specially characteristic of the lower subdivision of the Silurian system, are richest in genera, of which some of the commonest are *Diplograptus*, *Dicellograptus*, *Didymograptus*, and *Climacograptus*.

Corals must have swarmed on those parts of the Silurian sea-floor on which calcareous accumulations gathered, for their remains are abundant among the limestones, particularly in the upper division of the system. Among the tabulate forms are the genera *Favosites*, so characteristic in the Upper Silurian limestones of Europe and

America, *Chætetes, Thecia, Halysites* or chain coral, *Syringopora*, and *Tetradium*. The rugose corals are likewise abundant, some conspicuous genera being *Stauria, Cyathaxonia, Cyathophyllum, Zaphrentis, Petraia, Omphyma* (Fig. 327), *Strombodes, Ptychophyllum*, and *Acervularia* (Fig. 327). The echinoderms were represented by star-fishes (*Palæaster, Palæasterina, Palæocoma, Lepidaster*), brittle-stars (*Protaster, Eucladia*), many forms of crinoids (*Actinocrinus, Cyathocrinus, Glyptocrinus, Eucalyptocrinus, Taxocrinus*, &c.), and particularly by species of the extinct Palæozoic order of cystideans (*Echinosphærites, Sphæronites, Pleurocystites, Hemicosmites*). The annelides of the Silurian sea-bottom comprised representatives of both the tubicolar and errant orders. To the former belong the genera *Cornulites, Ortonia, Conchicolites, Serpulites*, and also the still living genus *Spirorbis*. The errant forms are known only by their burrows or trails which occur in immense profusion on the surfaces of shales and sandstones. Names have been given to these markings (*Arenicolites, Chondrites, Nereites, Scolithus*, &c.).

The crustacea of the period have been abundantly preserved and form some of the most familiar and distinctive fossils of the system. Within the last few years undoubted cirripedes have been found in the Silurian rocks of Britain, Bohemia, and North America (*Turrilepas, Anatifopsis*). Small ostracods abound in certain shales, some of the most frequent genera being *Entomis, Beyrichia, Primitia, Leperditia, Aristozoe, Orozoe, Callizoe*. The phyllopods, which, as we have seen, made their appearance in Cambrian times, continue to occur on scattered horizons, and generally not in great numbers, throughout the Silurian rocks; characteristic genera are *Caryocaris, Peltocaris, Discinocaris, Ceratiocaris, Dictyocaris, Cryptocaris*, and *Aptychopsis*. But by far the most prolific order is that of the trilobites (Fig. 323), which, beginning in the Cambrian, attained its maximum development in the Silurian, waned in the Devonian, and became extinct in the Carboniferous period. According to the census of Barrande in 1872 there were then 1579 known species. A few of the primordial genera continued to live on into Lower Silurian times, such as *Olenus, Agnostus*, and *Conocoryphe*. But many new genera made their appearance and continued to live through most of the Silurian period. In the lower division of the system, characteristic genera are *Asaphus, Amphion, Ampyx, Barrandia, Cybele, Ogygia, Remopleurides*, and *Trinucleus;* many genera are common to both the lower and upper formations (but usually with specific distinctions), such as *Acidaspis, Calymene, Cheirurus, Encrinurus, Homalonotus, Illænus, Lichas*, and *Phacops*. Towards the top of the system eurypterids make their appearance, and continue to occupy a prominent place until the Carboniferous period. The Silurian genera are *Pterygotus, Eurypterus, Slimonia, Stylonurus*, and *Hemiaspis*.

The polyzoa of Silurian times have been tolerably well preserved,

and present many peculiarities of structure. One of the most abundant genera is *Fenestella*, which ranges from Lower Silurian to Permian rocks; another, *Ptilodictya*, ascends into the Carboniferous system. Other genera are *Retepora, Paleschara*, and *Hippothoa*. So abundant are the brachiopods and so characteristic on the whole are the species of them occurring in certain Silurian zones or bands, that these fossils must be regarded as of special value for purposes of stratigraphical comparison. The old and still living genera *Discina, Lingula*, and *Crania* are found on different horizons in the Silurian series. Characteristic types are *Acrotreta. Atrypa, Leptæna, Meristella, Orthis, Pentamerus, Porambonites, Rhynchonella, Siphonotreta, Spirifera, Stricklandinia, Strophomena*, and *Triplesia*. Some of these

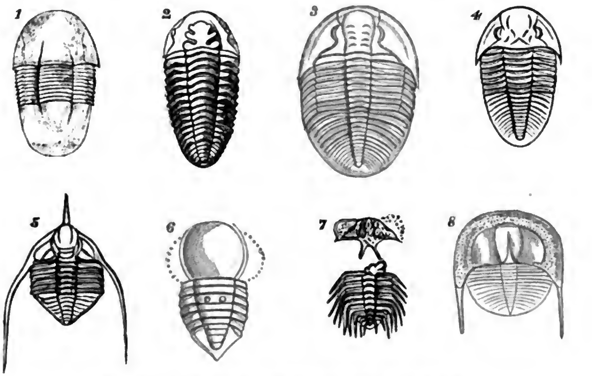

FIG. 323.—GROUP OF LOWER SILURIAN TRILOBITES.

1, Illænus Davisii (Salt.) ($\frac{1}{2}$); 2, Calymene brevicapitata (Portl.); 3, Ogygia Buchii (Brongn.) ($\frac{1}{2}$); 4, Asaphus tyrannus (Murch.) ($\frac{1}{11}$); 5, Ampyx nudus (Murch.) ($\frac{1}{2}$); 6, Æglina binodosa (Salt.); 7, Acidaspis Jamesii (Salt.); 8, Trinucleus Lloydii (Murch.).

are particularly distinctive of certain zones. Thus the *Pentameri* are so common in the so-called middle Silurian rocks in Britain that these strata received the name of the "Pentamerus beds" (Fig. 326). *Orthis* is most abundant in species in the lower part of the Silurian system: *Rhynchonella* and *Spirifera* occur chiefly in the upper. The lamellibranchs have been less abundantly preserved; some of their most frequent genera are the monomyarian *Ambonychia* (Fig. 328) and *Pterinea* and the dimyarian *Ctenodonta. Modiolopsis, Goniophora, Orthonota* (Fig. 328), *Cleidophorus* (Fig. 325), *Palæarca*, and *Redonia* (Fig. 324).

Of the gasteropods of the Silurian seas upwards of 1300 species have been named; some of the more frequent genera are *Acroculia*,

Cyclonema, Euomphalus, Helicotoma, Holopæa, Holopella, Murchisonia, Ophileta, Platyschisma, Pleurotomaria, Raphistoma, and *Subulites.* Some heteropod forms occur, *e.g. Bellerophon* and *Maclurea;* but pteropods are more frequent, being represented sometimes abundantly by the genera *Tentaculites* (regarded by some as an annelide), *Hyolithus* (or *Theca*), *Conularia*, and *Pterotheca.* That the salt waters of the Silurian era swarmed with cephalopods may be inferred from the fact that according to Barrande's census no fewer than 1622 species have been described. They are all tetrabranchiate. Some of the most abundant forms are straight shells, of which *Orthoceras* (Figs. 324, 328) is the type. This characteristically Palæozoic genus abounded in the Silurian period and many of its individuals attained a great size. Barrande has described upwards of 550 species from the basin of Bohemia. Of *Cyrtoceras,* in which the shell was curved, the same small area has yielded more than 330 species. *Phragmoceras* (Fig. 328) likewise possessed a curved shell, but with an aperture contracted in the middle. In *Ascoceras* the shell was globular or flask-shaped, with curiously curved septa; in *Lituites* (Fig. 328) it was curled like that of *Nautilus.* The two latter genera occur in Silurian rocks, but while *Lituites* never outlived the Silurian period, *Nautilus* is still a living denizen of the sea.

The first traces of vertebrate life make their appearance near the top of the Silurian system. They consist of the remains of fishes, the most determinable of which are the plates of placoderms (*Pteraspis, Coccosteus*). The bone-bed of the Ludlow rocks has also yielded certain curved spines which, under the name of *Onchus,* have been referred to a cestraciont, and some shagreen-like plates which have been supposed to be scales of placoid fishes (*Sphagodus, Thelodus*), and bodies like jaws with teeth which have been regarded as jaws of fishes (*Plectrodus*). It is possible, however, that some at least of these remains have been incorrectly determined, and may be crustacean. The Upper Silurian rocks have yielded, both in Europe and North America, great numbers of minute tooth-like bodies which were named "Conodonts" by their discoverer, Pander, and were supposed to be the teeth of such fishes as the lamprey, which possessed no other hard parts for preservation. These bodies have been also referred to different divisions of the invertebrata, their true position being still matter of dispute.

§ 2. Local Development.

Britain.[1]—In the typical area where Murchison's discoveries were first made he found the Silurian rocks divisible into two great and well-marked series, which he termed Lower and Upper. This classification

[1] See Murchison's "Silurian System," and "Siluria;" Sedgwick's "Synopsis" (cited p. 652); Ramsay's "North Wales" in *Memoirs of Geol. Surv.* vol. iii.; Etheridge, Address *Q. J. Geol. Soc.* 1881; numerous local memoirs in recent volumes of the *Quart. Journ. Geol. Soc.* and *Geol. Mag.*, particularly by Hicks, Ward, Hughes, Keeping, Lapworth, &c.

has been found to hold good over a large part of the world. The subjoined table shows the arrangement and nomenclature of the various subdivisions of the Silurian system :

		Feet.
Upper Silurian.	7. Ludlow group	1950
	6. Wenlock group	1600
	5. Upper Llandovery group	1500
Lower Silurian.	4. Lower Llandovery group	1000
	3. Bala and Caradoc group	6000
	2. Llandeilo group	2500
	1. Arenig or Stiper Stone group	4000
	Approximate average thickness	= 18,550

Lower Silurian.—1. *Arenig or Stiper Stone Group.*—These rocks consist of dark slates, shales, flags, and bands of sandstone. They are abundantly developed in the Arenig mountain, where, as originally described by Sedgwick, they contain masses of associated porphyry. Throughout that district they have been deposited at a time when streams of lava and showers of volcanic ashes were thrown out in great quantity from submarine vents. They contain an abundant suite of organic remains (63 genera and 150 species), of which only eleven genera and sixteen species are common to the Tremadoc beds below, while eight genera and nine species pass up into the next group. New genera of trilobites make their appearance in these rocks (*Æglina*, *Barrandea*, *Calymene*, *Homalonotus*, *Illænopsis*, *Illænus*, *Phacops*, *Placoparia*, *Trinucleus*). Eight species of pteropods (*Conularia*, *Theca*), eighteen species of brachiopods (*Lingula*, *Lingulella*, *Obolella*, *Discina*, *Siphonotreta*, *Orthis*), six lamellibranchs, four gasteropods, and five cephalopods have been found ; but the most abundant organisms are the graptolites, of which the Arenig rocks of St.

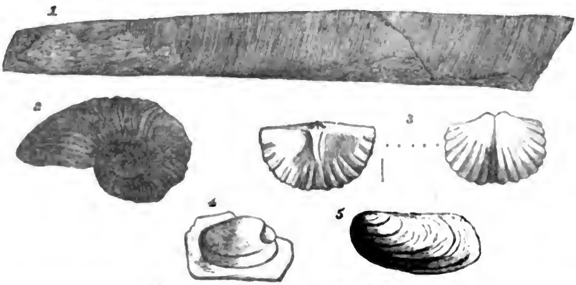

FIG. 324.—GROUP OF ARENIG FOSSILS.

1, Orthoceras cæreesiense (Hicks); 2, Bellerophon llanvirnensis (Hicks); 3, Orthis calligramma (Dalm.) (enlarged); 4, Redonia anglica (Salt.); 5, Palæarca amygdalus (Salt.).

David's, in Pembrokeshire, have yielded forty-two species, which belong to eighteen genera, including *Didymograptus*, *Tetragraptus*, *Diplograptus*, *Dendrograptus*, and *Callograptus*.[1] This sudden and great development

[1] Hicks, *Quart. Journ. Geol. Soc.* xxxi. 167. Hopkinson and Lapworth, *ibid.* p. 635 Etheridge, *ibid.* xxxvii. p. 89.

of these organisms gives a distinctive aspect to the Arenig rocks. Graptolites continue abundant in the overlying Llandeilo group, so that they form in Britain a convenient character by which to mark off the Cambrian from the Lower Silurian fauna.

A remarkable feature in the history of the Arenig rocks in Wales was the volcanic action during their formation, whereby vast piles of various felsitic or rhyolitic lavas and tuffs were erupted to the surface and interstratified with the contemporaneously deposited sediments. Some of the more important Welsh mountains consist mainly of these ancient volcanic materials—Cader Idris, the Arans, Arenig Mountain, and others.

2. *Llandeilo Group.*—These dark argillaceous and occasionally calcareous flagstones, sandstones, and shales were first described by Murchison as occurring at Llandeilo, in Carmarthenshire. They reappear near St. David's, on the coast of Pembrokeshire, and at Builth, in Radnorshire. Up to the present time they have yielded 80 genera and 175 species of fossils. Of these eight genera and nine species are common to the Arenig below, 38 genera and 73 species to the Caradoc and Bala above, while 34 genera and 93 species are peculiar. The hydrozoa are still abundant forms, certain dark shales being copiously charged with graptolites. Of crustacea 45 species belonging to 18 or 20 genera have been obtained. These include characteristic trilobites which do not range beyond this group—*Asaphus tyrannus, Barrandea Cordai, Calymene cambrensis, Cheirurus Sedgwickii, Ogygia Buchii, Trinucleus concentricus, T. Lloydii, T. favus.* The phyllopod *Peltocaris aptychoides* is also peculiar. The brachiopods number 34 species, including the genera *Acrotreta, Crania, Leptæna, Rhynchonella*, and *Strophomena*, which here make their first appearance. The lamellibranchs are represented by six species, the gasteropods by 12 (*Murchisonia, Cyclonema, Loxonema*), the heteropods by seven (*Bellerophon*), the pteropods by two (*Conularia, Theca*), the cephalopods by seven (*Orthoceras, Piloceras, Endoceras*).

3. *Caradoc and Bala Group.*—Under this name are placed the thick yellowish and grey sandstones of Caer Caradoc in Shropshire, and the grey and dark slates, grits, and sandstones round Bala in Merionethshire. In the Shropshire area some of the rocks are so shelly as to become strongly calcareous. In the Bala district the strata contain two limestones separated by a sandy and slaty group of rocks 1400 feet thick. The lower or Bala limestone (25 feet thick) has been traced as a variable band over a large area in North Wales. It is usually identified with the Coniston limestone of the Westmoreland region. The upper or Hirnant limestone (10 feet) is more local. Bands of volcanic tuff and large beds of various felsitic lavas occur among the Bala beds, and prove the contemporaneous ejection of volcanic products. These attain a thickness of several thousand feet in the Snowdon region.

A large suite of fossils, including 179 genera and 614 species, has been obtained from this group. The sponges are represented by *Sphærospongia* and other genera; the graptolites by *Diplograptus pristis, Monograptus* (*Graptolithus*) *priodon, M. Sedgwickii*, &c.; the corals by 40 species belonging to *Heliolites, Favosites, Monticulipora, Halysites, Petraia*, &c.; the echinoderms by encrinites of the genera *Cyathocrinus* and *Glyptocrinus*, by no fewer than 23 species of cystideans (*Echinosphærites, Sphæronites*, &c.), and

by star-fishes of the genera *Palæaster* and *Stenaster;* the annelides by *Serpulites*, and numerous burrows and tracks; the trilobites by 27 genera, of which the most important for their stratigraphical value are *Acidaspis* (8 species), *Ampyx* (6), *Agnostus* (5), *Asaphus* (6), *Calymene* (8), *Cheirurus* (6), *Homalonotus* (4), *Illænus* (13), *Lichas* (6), *Phacops*

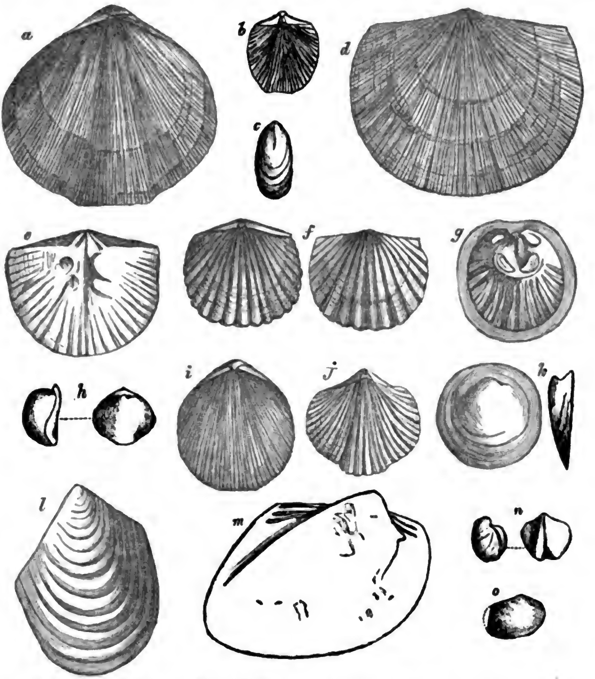

FIG. 325.—GROUP OF CARADOC FOSSILS.

a, Porambonites intercedens (Pander); *b*, Orthis hirnantensis (McCoy); *c*, Lingula longissima (Pander?); *d*. Strophomena grandis (Sby.); *e*, Orthis plicata (Sby.); *f*, Orthis calligramma (Dalm.); *g*, Crania divaricata (McCoy); *h*, Triplesia (?) maccoyana (Dav.); *i*, Atrypa (?) Headii (Billings) (?); *j*, Atrypa marginalis (Dalm.); *k*, Discina oblongata (Portl.); *l*, Ambonychia prisca (Portl.); *m*, Palæarca billingsiana (Salt.); *n*, Rhynchonella nana (Salt.); *c*, Cleidophorus ovalis (McCoy).

(13), *Remopleurides* (8); the ostracods by *Beyrichia*, *Leperditia*, *Cythere*, *Primitia*, and *Entomis;* the polyzoa by *Fenestella*, *Glauconome*, and *Ptilodictya;* the brachiopods by *Atrypa*, *Rhynchonella*, *Leptæna*, *Orthis* (41 species), *Strophomena* (19), *Discina*, and *Lingula;* the lamellibranchs by *Ctenodonta* (17 species), *Orthonota* (5), *Modiolopsis* (16), *Pterinea*

(6), *Ambonychia* (8), *Palæarca* (5); the gasteropods by *Murchisonia*, *Pleurotomaria*, *Raphistoma*, *Cyclonema*, *Euomphalus*, and *Holopea;* the pteropods by *Tentaculites*, *Conularia*, *Theca;* the heteropods by 1? species of *Bellerophon* and some forms of *Maclurea;* and the cephalopods by 47 species belonging to the genera *Orthoceras*, *Cyrtoceras*, *Lituites*, &c.

4. *Lower Llandovery Group.*—In North Wales the Bala beds about five miles S.E. of Bala Lake begin to be covered with grey grits, which gradually expand southwards until they attain a thickness of 1000 feet in South Wales. These overlying rocks are well displayed near the town of Llandovery, where they contain some conglomerate bands, and where Mr. Aveline detected an unconformability between them and the Bala group below them, so that the subterranean movements had already begun, which in Wales marked the close of the Lower Silurian period. Elsewhere they seem to graduate downwards conformably into that group. They cover a considerable breadth of country in Cardigan and Carmarthenshire, owing to the numerous undulations into which they have been thrown. Their chief interest lies in the transition which they present between the fauna of the Lower and Upper Silurian formations. They have yielded in all, according to Mr. Etheridge's census, 66 genera and 204 species of fossils, whereof 50 genera and 105 species are common to the Bala group below, and 45 genera and 104 species pass up into Upper Llandovery rocks above. Some of peculiar fossils are *Nidulites favus*, *Meristella crassa*, *M. angustifrons*, and *Murchisonia angulata*. Among the forms which come up from the Bala group and disappear here are the corals *Heliolites interstinctus*, *Petraia subduplicata*, and *Favosites aspera;* the trilobites *Lichas laxatus* and *Illænus Bowmanni;* the brachiopods *Orthis Actoniæ* and *O. insularis;* the gasteropods *Murchisonia gyrogonia* and *Cyclonema crebristria;* and the cephalopod *Orthoceras tenuicinctum*. But many of the Lower Silurian forms continue on into the Upper Llandovery beds. From the abundance of the peculiar brachiopods termed *Pentamerus* in the Lower, but still more in the Upper Llandovery rocks, these strata were formerly grouped together under the name of "Pentamerus beds." Though the same species are found in both divisions, *Pentamerus oblongus* is chiefly characteristic of the upper group and comparatively infrequent in the lower, while *Stricklandinia* (*Pentamerus*) *lens* abounds in the lower but appears more sparingly in the upper.

The Lower Silurian rocks, typically developed in Wales, extend over nearly the whole of Britain, though largely buried under more recent formations. They rise into the hilly tracts of Westmoreland and Cumberland, where they consist of the following subdivisions in descending order:

(Lower Llandovery not represented.)		
Coniston Limestone and Shale . .	=	Bala beds.
Volcanic series (green slates and porphyries): tuffs and lavas without ordinary sedimentary strata except at base, 12,000 ft.	=	Part of Bala, whole of Llandeilo, and perhaps part of Arenig formation.
Skiddaw Slates, 10,000 or 12,000 ft., base not seen	=	Arenig, with perhaps Tremadoc and Lingula Flags.

Apart from the massive intercalation of volcanic rocks these strata present considerable lithological and palæontological differences from the

typical subdivisions in Wales. The Skiddaw slates are black or dark-grey argillaceous, and in some beds sandy, rocks, often much cleaved, though seldom yielding workable slates, sometimes soft and black like Carboniferous shale. As a rule they are singularly unfossiliferous, but in some of their less cleaved and altered portions they have yielded about 40 species of graptolites (chiefly of the genera *Didymograptus*, *Diplograptus*, *Dichograptus*, *Tetragraptus*, *Phyllograptus*, and *Climacograptus*), *Lingula brevis*, traces of annelides, a few trilobites (*Æglina*, *Agnostus*, *Asaphus*, &c.), some phyllopods (*Caryocaris*), and remains of plants (*Buthotrephis*, &c.). In many places the slates have been metamorphosed, passing into chiastolite-slate, mica-schist, andalusite-schist, &c., with protrusions of granite, syenite, and other crystalline rocks (p. 579). Towards the close of the long period represented by the Skiddaw slates, volcanic action manifested itself, first by intermittent showers of ashes and streams of lava, which were interstratified with the ordinary marine sediment, and then by a more powerful and continuous series of explosions, whereby a huge volcanic mountain or group of cones was piled up above the sea-level. The length of time occupied by this volcanic episode in Cumbrian geology may be inferred from the fact that all the Llandeilo and nearly all the Bala beds are absent here. The volcanic island slowly sank into a sea where Bala organisms flourished. Among these we find such familiar Bala species as *Favosites fibrosa*, *Heliolites interstinctus*, *Cybele verrucosa*, *Leptæna sericea*, *Orthis Actoniæ*, *O. biforata*, *O. caligramma*, *O. elegantula*, *O. porcata*, and *Strophomena rhomboidalis*. These organisms and their associates gathered on the submerged flanks of the sinking volcano into a bed of limestone—the Coniston limestone—which can still be traced for many miles through the Westmoreland hills, as the Bala limestone which it represents can be followed through the volcanic tracts of North Wales. The Coniston limestone is covered by certain flags and grits which from their organic remains are referred to the Upper Silurian series.

In the south of Scotland, according to the detailed researches of the Geological Survey, the Lower Silurian formations are represented by the subjoined groups of strata in descending order:

Sandstones and conglomerates, Girvan valley . .	= Llandovery.
Conglomerates, grits, shales, and lenticular bands of limestone, Peeblesshire, Dumfriesshire, S.W. Ayrshire, sometimes 2000 ft.	= Caradoc or Bala.
Carsphairn group, coarse pebbly grits and greywacke, 1200 ft.	= Llandeilo (14,000 ft.).
Upper Black Shale, with graptolites, 550 ft. . .	
Lowther group, olive, grey, and blue shales, and sandstones, 4000 ft.	
Dalveen group, greywacke and shale, with band of fine conglomerate, 3500 ft.	
Queensberry group, massive greywackes and grits, with occasional conglomerate bands and some shales, 4500 ft.	
Lower or Moffat Black Graptolite Shale group, 200–400 ft.	
Ardwell group, brown flags, greywackes, and shales, sometimes purplish and red; base not seen . .	

As a whole these strata are singularly barren of organic remains. Most of the fossils which the Llandeilo groups contain lie in the bands of

dark anthracitic shale which have been traced across nearly the whole breadth of the country. These shales, crowded with graptolites of recognizable Llandeilo forms (*Climacograptus teretiusculus*, *Diplograptus pristis*, and *Graptolithus sagittarius* being particularly abundant), were deposited over wide areas of sea-bottom. It is remarkable that wherever they appear the graptolites come with them, as if these organisms could only flourish on the black carbonaceous mud. The persistence of the graptolitic fauna is shown by the fact that many of the same species occur in the upper black shales at a vertical distance of more than 10,000 feet above the horizon of the lower shales (p. 629). Crustacea are exceedingly rare, but two phyllopods, *Discinocaris Browniana* and *Peltocaris aptychoides*, occur; while from Dumfriesshire two obscure trilobites are referred doubtfully to *Encrinurus* and *Phacops*. The vast thickness of sandy, gritty, and shaly unfossiliferous strata is the distinguishing feature of the Lower Silurian series in the south of Scotland.[1] The Caradoc or Bala group lies unconformably upon the upper parts of the Llandeilo rocks. It contains in the eastern districts some calcareous conglomerates which here and there swell out into local masses of limestone. In the south-west of Ayrshire the limestones attain considerable dimensions. In these calcareous bands numerous Caradoc species have been found, among them *Cheirurus gelasinosus*, *Encrinurus punctatus*, with species of *Illænus* and *Asaphus*, *Orthis calligramma*, *O. confinis*, *Leptæna sericea*, *Maclurea*, and such corals as *Heliolites*, *Favosites*, *Omphyma*, and *Strephodes*. In the same district certain shales and sandstones full of Caradoc fossils are overlaid with sandstones, shales, and conglomerates containing *Pentamerus oblongus*, *Atrypa hemispherica*, *Meristella angustifrons*, *Lichas laxatus*, *Petraia elongata*, *Nidulites favus*, and numerous other fossils which indicate the horizon of the Llandovery rocks.

The Highlands of Scotland, as above (p. 583) stated, consist mainly of crystalline rocks—gneiss, mica-schist, chlorite-schist, clay-slate, quartz-rock, schistose flagstone, and many others, which from the discovery of recognizable fossils near their base have been shown to be metamorphosed Lower Silurian rocks. As this deduction possesses very great importance in theoretical geology, particularly in relation to the history of metamorphism and metamorphic rocks, it is desirable that the true geological horizon of fossils found below so vast a pile of crystalline schists should be precisely determined. Fortunately the number and good preservation of the specimens allowed the determination to be satisfactorily made by Salter, who declared his conviction that they were unequivocally Lower Silurian, and bore a most remarkable resemblance to a group of fossils from the Lower Silurian rocks of North America. Five of the species he regarded as identical with known American forms (*Orthoceras arcuoliratum*, Hall; *Orthis striatula*, Emmons; *Ophileta compacta*, Salt.? *Murchisonia gracilis*, Hall; *M. bellicincta*, Hall), 4 as representative, 3 doubtful, and 1 new genus, found also in Canada. "That this truly North American assemblage," he remarks, "should be found in the ex-

[1] Mr. Charles Lapworth, who has devoted much time to the study of the graptolites of these rocks, has come to the conclusion that what is here termed the Moffat Shale group, and regarded as merely a subordinate member of a thick series of sandy and generally unfossiliferous strata, represents the whole series of strata from the Llandeilo up into the Upper Silurian formations; that is to say, somewhere about a half of the whole of the Silurian system is contained in a group of shales and sandstones, sometimes less than 200 feet thick!

treme north of Scotland on the same parallel as the Canadian,—that species of *Maclurea* and *Raphistoma*, resembling those of the St. Lawrence basin, and *Orthocerata* bearing large siphuncles, like those of North America, Scandinavia, and Russia, should occur in Scotland, and yet be scarcely known further south, is at least suggestive of a geographical distribution—perhaps even of climatal conditions—not very unlike that of more modern times."[1] From this palæontological decision it follows that the overlying conformable schistose series of the Scottish Highlands is a mass of metamorphosed Silurian strata.

In the south-east of Ireland, grey, greenish, and purple grits, and grey and dark shales lie unconformably upon the Cambrian rocks, and contain a few fossils of Landeilo age. They present interstratified beds of tuff and felsitic lavas indicating contemporaneous volcanic action. In the north-east of the island a broad belt of Lower Silurian rocks runs from the coast of Down into the heart of Roscommon and Longford. This belt is evidently a prolongation of that in the southern uplands of Scotland. It is marked by the occurrence of similar dark anthracitic shales crowded with graptolites. The richest fossiliferous localities among the Irish Lower Silurian rocks are found at the Chair of Kildare, Portrane near Dublin, Pomeroy in Tyrone, and Lisbellan in Fermanagh, where small protrusions of the older rocks rise as oases among the surrounding later formations. Portlock brought the northern and western localities to light, and Murchison pointed out that, while a number of the trilobites (*Trinucleus*, *Phacops*, *Calymene*, *Illænus*), as well as the simple plated *Orthidæ*, *Leptænæ*, and *Strophomenæ*, some spiral shells, and many *Orthocerata*, are specifically identical with those from the typical Caradoc and Bala beds of Shropshire and Wales, yet they are associated with peculiar forms, first discovered in Ireland, and very rare elsewhere in the British Islands. Among these distinctive fossils he cites the trilobites, *Remopleurides*, *Harpes*, *Amphion*, and *Bronteus*, with smooth forms of *Asaphus* (*Isotelus*), which, though abundant in Ireland and America, seldom occur in Wales or England, and never on the Continent.[2]

In the north and west of Ireland a large area of surface is occupied by crystalline rocks—gneiss, schists, quartz-rocks, limestone, granite, &c.—which are manifestly a continuation of those of the Highlands of Scotland. They run south-westward parallel with the belt of unaltered Lower Silurian rocks from which, in some places, as in county Tyrone, they are only a few miles distant. The district of Pomeroy, so rich in Silurian fossils, promises to afford the greatest light on the interesting but difficult problem of the metamorphism of the Lower Silurian rocks of the Scottish Highlands and the north-west of Ireland. It will be seen from the evidence furnished by the sections in West Mayo (p. 685) that the metamorphism must have taken place prior to the deposition of the Upper Silurian rocks of the west of Ireland.

Upper Silurian.—The series of rocks in the British Islands classed as Upper Silurian occurs in two very distinct types. So great indeed is the contrast between these types that it is only by a comparison of organic remains that the whole has been grouped together as the deposits of one great geological period. In the original region described by Murchison, and from which his type of the system was taken, the strata are

[1] *Quart. Journ. Geol. Soc.* xx. 381.
[2] "Siluria," p. 174.

comparatively flat, soft, and unaltered, consisting mainly of somewhat incoherent sandy mudstone and shale, with occasional bands of limestone. But as these rocks are followed into North Wales, they are found to swell out into a vast series of grits and shales, so like portions of the hard altered Lower Silurian rocks that, save for the evidence of fossils, they would naturally be grouped as part of that more ancient series. In Westmoreland and Cumberland, and still further north in the border counties of Scotland, also in the south-west of Ireland, it is the North Welsh type which prevails, so that in Britain the general lithological characters and minute palæontological subdivisions ascertained in the original Silurian district are almost confined to that limited region, while over the rest of the British area for thousands of square miles the hard sandy and shaly type of North Wales is prevalent.

Taking first the Silurian tract of the west of England, and the east and south of Wales, we find a decided unconformability separating the Lower from the Upper Silurian deposits. In some places the latter steal across the edges of the former, group after group, till they lie directly upon the Cambrian rocks. Indeed, in one district between the Longmynd and Wenlock Edge, the base of the Upper Silurian rocks is found within a few miles to pass from the Caradoc group across to the Lower Cambrian rocks. It is evident, therefore, that in the Welsh region very great disturbance and extensive denudation preceded the commencement of the deposition of the Upper Silurian rocks. As Sir Andrew C. Ramsay has pointed out, the area of Wales, previously covered by a wide though shallow sea, was ridged up into a series of islands, round the margin of which the conglomerates at the base of the Upper Silurian series began to be laid down. This took place during a time of submergence, for these conglomeratic and sandy strata are found creeping up the slopes and even capping some of the hills, as at Bogmine, where they reach a height of 1150 feet above the sea.[1] The subsidence probably continued during the whole of the interval occupied by the deposition of the Upper Silurian strata, which were thus piled to a depth of from 3000 to 5000 feet over the disturbed and denuded platform of Lower Silurian rocks.

Arranged in tabular form, the subdivisions of the Upper Silurian rocks of Wales and the adjoining counties of England are in descending order as follows:

Base of Old Red Sandstone.

3. Ludlow group.	Tilestones. Upper Ludlow Rock. Aymestry Limestone. Lower Ludlow Rock.	
2. Wenlock group	Wenlock or Dudley Limestone . . . Wenlock Shale . . . . . . Woolhope or Barr Limestone and Shale . Tarannon Shale	= Denbighshire Grits of North Wales.
1. Upper Llandovery group	May Hill Sandstones.	

Lower Llandovery Rocks.

1. *Upper Llandovery group.—May Hill Sandstones.*—The position of these rocks as the true base of the Upper Silurian groups was first shown in 1853 by Sedgwick, who named them the May Hill Sandstone from the locality in Gloucestershire where they are so well displayed

[1] Ramsay, *Physical Geology and Geography of Britain*, p. 91.

Appearing on the coast of Pembrokeshire at Marloes Bay, they range across South Wales until they are overlapped by the Old Red Sandstone. They emerge again in Carmarthenshire, and trend north-eastward as a narrow strip at the base of the Upper Silurian series, from a few feet to 1000 feet or more in thickness, as far as the Longmynd, where, as a marked conglomerate wrapping round that ancient Cambrian ridge, they disappear. In the course of this long tract they pass successively and unconformably over Lower Llandovery, Caradoc, Llandeilo, and

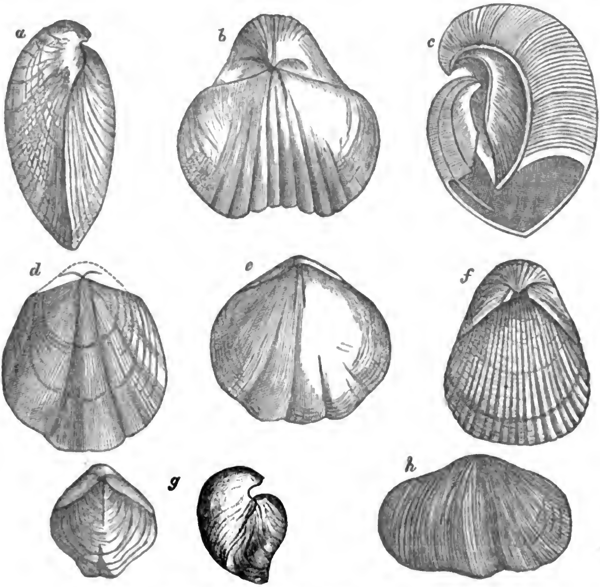

FIG. 326.—GROUP OF PENTAMERI FROM LLANDOVERY ROCKS.

a, Pentamerus oblongus (Sby.); *b*, P. galeatus (Dalm.); *c*, P. Knightii (Sby.); *d*, P. oblongus (Sby.); *e*, P. rotundus (Sby.) (?); *f*, P. Knightii (small specimen); *g*, P. linguifer (Sby.); *h*, P. undatus (Sby.).

Cambrian rocks. They consist of yellow and brown ferruginous sandstones, often full of shells, which are apt to weather out and leave casts. Their lower parts are commonly conglomeratic, the pebbles being largely derived from older parts of the Silurian system. Here and there, where the organic remains become extraordinarily abundant, the strata pass into a kind of sandy limestone, known as the "Pentamerus limestone," from the numbers of this brachiopod contained in it. The fossils found in the May Hill Sandstones number 91 genera and 261 species, of which only 136 species are confined to this group.

Among the fossils are some traces of fucoids; sponges (*Cliona*, a burrowing form like the modern *Cliona*); the widely-diffused *Monograptus (Graptolithus) priodon*; a number of corals (*Petraia, Heliolites, Favosites, Halysites, Syringopora*, &c.); a few crinoids and the earliest known sea-urchins (*Palæchinus*); the genus *Tentaculites*, by some naturalists classed with the pteropods, by others with the annelides, is particularly abundant; a number of trilobites, of which *Phacops Stokesii, P. Weaveri, Encrinurus punctatus, Calymene Blumenbachii, Proëtus Stokesii*, and *Illænus Thomsoni* are common; numerous brachiopods, as *Atrypa hemispherica, A. reticularis, Pentamerus oblongus, Stricklandinia lirata, S. lens, Leptæna transversalis, Orthis calligramma, O. elegantula, O. reversa, Strophomena compressa, S. pecten*, and *Lingula parallela;* lamellibranchs of the mytiloid genera *Orthonota, Mytilus*, and *Modiolopsis*, with forms of *Pterinea, Ctenodonta*, and *Lyrodesma;* gasteropods, particularly the genera *Acroculia, Raphistoma, Murchisonia, Pleurotomaria, Cyclonema, Holopella;* heteropods, particularly the species *Bellerophon dilatatus, B. trilobatus*, and *B. carinatus;* and cephalopods, chiefly *Orthocerata*, with some forms of *Actinoceras, Cyrtoceras, Tretoceras*, and *Phragmoceras*, and the old species *Lituites cornu-arietis*.

2. *Wenlock group.*—This suite of strata includes the larger part of the known Upper Silurian fauna of Britain, as it has yielded no fewer than 165 genera and 530 species. In the typical Silurian area of Murchison, it consists of two limestone bands (Woolhope and Wenlock), separated by a thick mass of shale (Wenlock Shale). The following subdivisions in ascending order are recognized.

(*a.*) *Tarrannon Shale.*—Above the Upper Llandovery beds comes a very persistent zone of fine, smooth, light grey or blue slates, which has been traced down the whole length of Wales from the mouth of the Conway into Carmarthenshire. These rocks, termed the "paste-rock" by Sedgwick, have an extreme thickness of 1000 to 1500 feet. Poor in organic remains, their chief interest lies in the fact that the persistence of so thick a band of rock between what were supposed to be continuous and conformable formations should have been unrecognized until it was proved by the detailed mapping of the Geological Survey.

(*b.*) *Woolhope Limestone.*—In the original typical Upper Silurian tract of Shropshire, and the adjacent counties, the Upper Llandovery rocks are overlaid by a local group of grey shales containing nodular limestone which here and there swells out into beds having an aggregate thickness of 30 or 40 feet. These strata are well displayed in the picturesque valley of Woolhope in Herefordshire, which lies upon a worn quaquaversal dome of Upper Silurian strata rising in the midst of the surrounding Old Red Sandstone. They are seen likewise to the north-west at Presteign, Nash Scar, and Old Radnor in Radnorshire, and to the east and south in the Malvern Hills (where they include a great thickness of shale below the limestone), and May Hill in Gloucestershire. These strata have yielded many characteristically Upper Silurian fossils, including 13 genera and 24 species of crustacea and 17 genera and 56 species of brachiopods. Among the common forms may be mentioned *Bumastus Barriensis, Homalonotus delphinocephalus, Phacops caudatus, Atrypa reticularis, Orthis calligramma, Strophomena imbrex, Rhynchonella borealis, R. Wilsoni, Euomphalus sculptus, Orthoceras annulatum.*

It is a feature of the older Palæozoic limestones to occur in a very lenticular form, swelling in some places to a great thickness and rapidly

dying out, to reappear again perhaps some miles away with increased proportions. This local character is well exhibited by the Woolhope limestone. Where it disappears, the shales underneath and intercalated with it join on continuously to the overlying Wenlock shale, and no line for the Woolhope sub-group can then be satisfactorily drawn. The same discontinuity is strikingly traceable in the Wenlock limestone, to be immediately referred to.

(*c.*) *Wenlock Shale.*—This is a series of grey and black fine shales, traceable from the banks of the Severn near Coalbrook Dale across Radnorshire to near Carmarthen—a distance of about 90 miles. The

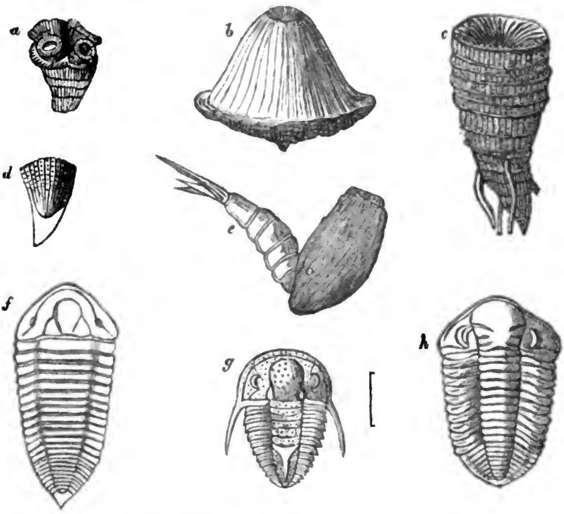

FIG. 327.—UPPER SILURIAN CORALS AND CRUSTACEANS.

a, Acervularia ananas (Linn.); *b*, Ptychophyllum patellatum (Schloth.) (½); *c*, Omphyma turbinatum (Linn.) (½); *d*, Petraia bina (Lons.); *e*, Ceratiocaris papilio (Salt.); *f*, Homalonotus delphinocephalus (Green) (½); *g*, Cyphaspis megalops (McCoy); *h*, Phacops Downingiæ (Murch.).

same strata reappear in the protrusions of Upper Silurian rocks which rise out of the Old Red Sandstone plains of Gloucestershire, Herefordshire, and Monmouthshire. In the Malvern Hills they were estimated by Professor Phillips to reach a thickness of 640 feet, but towards the north they thicken out to 1000 or even 1400 feet. On the whole the fossils are identical with those of the overlying limestone. The corals, however, so abundant in that rock, are here comparatively rare. The brachiopods (of the genera *Leptæna*, *Orthis*, *Strophomena*, *Atrypa*, and *Rhynchonella*) are generally of small size—*Orthis biloba*, *O. hybrida*, and the large flat *O. rustica* being characteristic. Of the higher mollusca

thin-shelled forms of *Orthoceras* are specially abundant. Among the trilobites, *Encrinurus punctatus*, *E. variolaris*, *Calymene Blumenbachii*, *C. tuberculosa*, *Phacops caudatus*, and *P. longicaudatus* are common. The *Monograptus* (*Graptolithus*) *priodon*, so frequent among the Bala beds of the Lower Silurian series, also occurs in the Wenlock shale; while *M.* (*Graptolithus*) *Flemingii* is here a characteristic species.

(*d.*) *Wenlock Limestone.*—This is a thick-bedded, sometimes flaggy, usually more or less concretionary limestone, grey or pale pink, often highly crystalline, occurring in some places as a single massive bed, in others as two or more strata separated by grey shales, the whole forming a thickness of rock ranging from 100 to 300 feet. As its name denotes, this zone is typically developed along Wenlock Edge in Shropshire, where it runs as a prominent ridge for fully 20 miles; also between Aymestry and Ludlow. It likewise appears at the detached areas of Upper Silurian strata above referred to, being specially well seen near Dudley (whence it is often spoken of as the Dudley limestone), Woolhope, Malvern, May Hill, and Usk in Monmouthshire.

A distinguishing characteristic of the Wenlock limestone is the abundance and variety of its corals, of which no fewer than 25 genera and 76 species have been described, of which 41 species are peculiar to the Wenlock group. The rock seems indeed to have been formed in part by massive sheets and bunches of coral. Characteristic species are *Halysites catenularia*, *Heliolites interstinctus*, *H. tubulatus*, *Alveolites Labechei*, *Favosites aspera*, *F. fibrosa*, *F. gothlandica*, *Cœnites juniperinus*, *Syringopora fascicularis*, and *Omphyma turbinatum*. The crinoids are also specially abundant, and often beautifully preserved: 20 genera make their first appearance in the Wenlock group, and 17 are confined to it, among the 65 species which have been named, *Periechocrinus moniliformis* is one of the most frequent; others being *Crotalocrinus rugosus*, *Cyathocrinus goniodactylus*, and *Marsupiocrinus cœlatus*. Several cystideans occur, of which one is *Pseudocrinites quadrifasciatus*. The annelides number 34 species. The crustaceans include numerous trilobites, among which we miss some of the persistent Lower Silurian genera, such as *Asaphus*, *Ogygia*, and *Trinucleus*, none of which ascend into the Wenlock group. The most abundant trilobite is the long-lived *Calymene Blumenbachii*, which ranges from the Llandeilo flags up to near the top of the Upper Silurian formations. It occurs abundantly at Dudley, where it received the name of the "Dudley Locust." Other common forms are *Encrinurus punctatus*, *E. variolaris*, *Phacops caudatus*, *P. Downingiæ*, *P. Stokesii*, *Bumastus Barriensis*, *Homalonotus delphinocephalus*, and *Cheirurus bimucronatus*. One of the most remarkable features in the crustaceous fauna is the first appearance of the merostomata, which are represented by *Eurypterus punctatus*, *Hemiaspis horridus*, and *Pterygotus problematicus*. The brachiopods continue to be abundant, 21 genera and 96 species having up to this time been enumerated; among typical species may be noted *Atrypa reticularis*, *Meristella tumida*, *Spirifera elevata*, *S. plicatella*, *Rhynchonella borealis* (very common), *R. cuneata*, *R. Wilsoni*, *Orthis elegantula*, *O. rustica*, *Strophomena rhomboidalis*, and *Pentamerus galeatus*. The lamellibranchs are represented by 43 species; among these several species of *Pterinea*, *Cardiola*, and *Cucullella* are abundant, with *Grammysia cingulata*, and some species of *Modiolopsis* and *Ctenodonta*. The gasteropods are marked by species

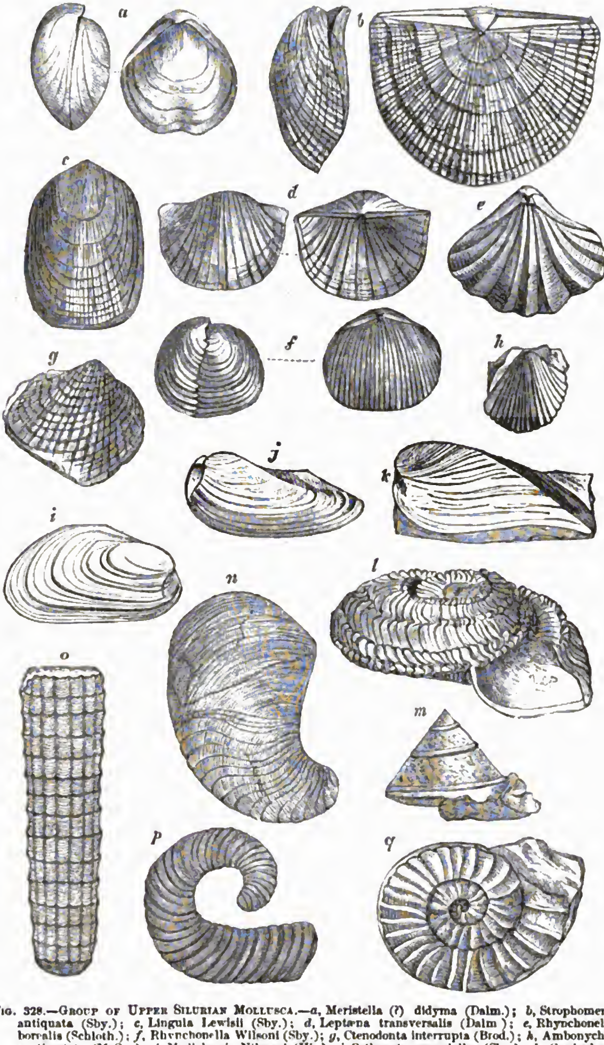

FIG. 328.—GROUP OF UPPER SILURIAN MOLLUSCA.—*a*, Meristella (?) didyma (Dalm.); *b*, Strophomena antiquata (Sby.); *c*, Lingula Lewisii (Sby.); *d*, Leptæna transversalis (Dalm.); *e*, Rhynchonella borealis (Schloth.); *f*, Rhynchonella Wilsoni (Sby.); *g*, Ctenodonta interrupta (Brod.); *h*, Ambonychia acuticostata (McCoy); *i*, Modiolopsis Nilssoni (His.); *j*, Orthonota amygdalina (Sby.); *k*, Goniophora cymbæformis (Sby.); *l*, Euomphalus rugosus (Sby.); *m*, Trochus cælatus (McCoy) (⅔); *n*, Phragmoceras ventricosum (Sby.) (½); *o*, Orthoceras annulatum (Sby.) (½); *p*, Lituites giganteus (Sby.) (½); *q*, Lituites articulatus (Sby.).

of *Euomphalus*, *Murchisonia*, *Holopella*, *Pleurotomaria*, *Acroculia*, *Cyclonema*. The cephalopods are confined to five genera, *Lituites*, *Actinoceras*, *Cyrtoceras*, *Orthoceras*, and *Phragmoceras*; of these the orthoceratites are by far the most abundant both in species and individuals. *Orthoceras annulatum* is the most common form. The pteropods appear in the beautiful and very abundant *Conularia Sowerbyi*, and the heteropods in the common and characteristic *Bellerophon Wenlockensis*.

3. *Ludlow Group.*—This series of stata consists essentially of shales, with occasionally a calcareous band in the middle. It graduates downward into the Wenlock group, so that when the Wenlock limestone disappears, the Wenlock and Ludlow shales form one continuous argillaceous formation, as they do where they stretch to the south-west through Brecon and Carmarthen: The Ludlow rocks, typically seen between Ludlow and Aymestry, appear likewise at the detached Silurian areas from Dudley to the mouth of the Severn. They were grouped by Murchison into three zones. Their fauna numbers at present nearly 400 species, of which 129 are also found in the Wenlock group.

(*a*.) *Lower Ludlow Rock.*—This is a group of soft dark-grey to pale greenish-brown or olive sandy shales, often with calcareous concretions. Much of the rock, however, presents so little fissile structure as to get the name of mudstone, weathering out into concretions which fall to angular fragments as the rock crumbles down. It becomes more sandy and flaggy towards the top. From the softness of the shales this zone of rock has been extensively denuded, and the Wenlock limestone rises up boldly from under it.

An abundant suite of fossils has been yielded by these shales. Eight species of star-fishes, belonging to the genera *Protaster* (like the brittle-stars of the British seas), *Palæodiscus*, and *Palæocoma*. A few graptolites (eight species belonging to *Graptolithus* or *Monograptus*) occur, particularly the persistent *Monograptus* (*Graptolithus*) *priodon* (common), *M. colonus*, and *M. Flemingii*. A few corals occur in the Lower Ludlow rock, all of species that had already appeared in the Wenlock limestone, but the conditions of deposit were evidently unfavourable for their growth. The trilobites are less numerous than in older beds; they include the venerable *Calymene Blumenbachii*, *Phacops caudatus*, and its still longer-tailed variety *P. longicaudatus*; also *Acidaspis Brightii*, *Homalonotus delphinocephalus*, and *Cyphaspis megalops*. But other forms of crustacean life occur in some number. As the trilobites begin to wane, numerous phyllopods appear, the genus *Ceratiocaris* being represented by ten or more species. Still more remarkable, however, was the increasing importance of the merostomatous crustaceans. Though brachiopods are not scarce, hardly any seem to be peculiar to the Lower Ludlow rock; of the 38 known species 33 occur in the Wenlock group. *Rhynchonella Wilsoni*, *Spirifera exporecta*, *Strophomena euglypha*, *Atrypa reticularis*, and *Chonetes minima* are not infrequent. Among the more frequently recurring species of lamellibranchs the following may be named—*Cardiola interrupta*, *C. striata*, *Orthonota rigida*, *O. semisulcata*, and a number of species of *Pterinea*. The orthoceratites are numerous, as *Orthoceras Ludense*, *O. subundulatum*, also species of *Phragmoceras* and *Lituites*. The numbers of these straight and curved cephalopods form one of the distinguishing features of the zone. At one locality, near Leintwardine in Shropshire,

which has been prolific in Lower Ludlow fossils, particularly in star-fishes and eurypterid crustaceans, a fragment of the fish *Scaphaspis* (*Pteraspis*) *ludensis* was discovered in 1859. This is the earliest trace of vertebrate life yet detected. It is interesting to note that this fish does not stand low in the scale of organization, but has affinities with our modern sturgeon.

(*b.*) *Aymestry Limestone*—a dark grey somewhat earthy concretionary limestone in beds from 1 to 5 feet thick. Where at its thickest it forms a conspicuous feature, rising above the soft and denuded Lower Ludlow shales, and, owing to the easily removable nature of some fuller's earth on which it lies, it has here and there been dislocated by large landslips. It is still more inconstant than the Wenlock limestone. Though well developed at Aymestry it soon dies away into bands of calcareous nodules, which finally disappear, and the lower and upper divisions of the Ludlow group then come together. The organic remains at present known number 53 genera and 84 species, which for the most part are identical with Wenlock forms. It is evident that the organisms which flourished so abundantly in the clear water in which the Wenlock limestone was accumulated continued to live outside the area of deposit of the Lower Ludlow rock and reappeared in that area when the conditions for their existence there returned during the deposition of the Aymestry limestone. The most characteristic fossil of the latter rock is the *Pentamerus Knightii;* other common forms are *Rhynchonella Wilsoni*, *Lingula Lewisii*, *Strophomena euglypha*, *Bellerophon dilatatus*, *Pterinea Sowerbyi*, with many of the same shells, corals, and trilobites found in the Wenlock limestone. Indeed, as Murchison has pointed out, except in the less number of species and the occurrence of some of the shells more characteristic of the Upper Ludlow zone, there is not much palæontological distinction between the two limestones.[1]

(*c.*) *Upper Ludlow Rock.*—In the original Silurian district described by Murchison, the Aymestry limestone is covered by a calcareous shelly band full of *Rhynchonella navicula*, sometimes 30 or 40 feet thick. This layer is succeeded by grey sandy shale or mudstone, often weathering into concretions, as in the Lower Ludlow zone, and assuming externally the same rusty-brown or greyish olive-green hue. Its harder beds are quarried for building stone; but the general character of the deposit, like that of the argillaceous portions of the Upper Silurian formations as a whole in the typical district of Siluria, is soft, incoherent, and crumbling, easily decomposing once more into the original mud, and presenting in this respect a contrast to the hard, fissile, and often slaty shales of the Lower Silurian series. Many of the sandstone beds are crowded with ripple-marks, rill-marks, and annelid-trails, indicative of the shallow littoral waters in which they were deposited. One of the uppermost sandstones is termed the "Fucoid Bed," from the number of its cylindrical sea-weed-like stems. It likewise contains numerous inverted pyramidal bodies, which are believed to be casts of the cavities made in the muddy sand by the rotatory movement of crinoids rooted and half buried in the micaceous mud.[2] At the top of the Upper Ludlow Rock near the town of Ludlow, a brown layer occurs from a quarter of an inch to three or four inches in thickness, full of fragments of fish, *Pterygotus*, and shells. This layer, termed the "Ludlow Bone-

[1] *Siluria*, p. 130. [2] *Op. cit.* p. 133.

bed," is the oldest from which any considerable number of vertebrate remains has been obtained. In spite of its insignificant thickness it has been detected at numerous localities from Ludlow as far as Pyrton Passage, at the mouth of the Severn—a distance of 45 miles from north to south, and from Kington to Ledbury and Malvern—a distance of nearly 30 miles from west to east; so that it probably covers an area (now largely buried under Old Red Sandstone) not less than 1000 square miles in extent. Yet it appears never to exceed and usually to fall short of a thickness of 1 foot. Fish remains, however, are not confined to this horizon, but have been detected in strata above the original bone-bed at Ludlow. The higher parts of the Ludlow rock consist of fine yellow sandstone and harder grits known as the Downton sandstone. Originally the whole of these flaggy upper parts of the Ludlow group were called "Tilestones" by Murchison, and being often red in colour were included by him as the base of the Old Red Sandstone, into which they gradually and conformably ascend. Undoubtedly they show the gradual change of physical conditions which took place at the close of the Silurian period in the west of England, and brought in the deposits of the Old Red Sandstone. But as their organic contents are still unequivocally those of the Ludlow group, they are now classed as the uppermost zone of the Silurian system.

A considerable suite of organic remains has been obtained from the Upper Ludlow rock, which on the whole are the same as those in the zones underneath. Vegetable remains, some of which seem to be fucoids, but most of which are probably terrestrial and lycopodiaceous, abound in the Downton sandstone and passage-beds into the Old Red Sandstone. Some minute globular bodies, doubtfully referred to the sporangia of a lycopod (***Pachytheca***), occur with some other plant remains (***Pachysporangium***, ***Actinophyllum***, ***Chondrites***, a beautiful sea-weed). Corals, as might be supposed from the muddy character of the deposit, seldom occur, though Murchison mentions that the encrusting form ***Alveolites fibrosus*** may not infrequently be found enveloping shells, ***Cyclonema corallii*** and ***Murchisonia corallii*** being, as their names imply, its favourite habitats. All the corals of these and the other divisions of the Ludlow group are also Wenlock species. Some annelides (***Serpulites longispinus***, ***Cornulites serpularius***, and ***Trachyderma coriacea***) are not uncommon. The crustacea are represented in the Upper Ludlow rock by 23 genera and 71 species, and in the whole Ludlow group by 29 genera and 97 species, including ostracods (***Beyrichia Klœdeni***, ***Leperditia marginata***, ***Entomis tuberosa***), phyllopods (16 species, ***Ceratiocaris***, ***Dictyocaris***), and eurypterids (***Eurypterus*** 10 species, ***Hemiaspis*** 6, ***Pterygotus*** 9, ***Slimonia*** 3, ***Stylonurus*** 3, ***Himantopterus*** 1). The trilobites have still further waned in the Upper Ludlow rock, though ***Homalonotus Knightii***, ***Encrinurus punctatus***, ***Phacops Downingiæ***, and a few others still occur, and even the persistent ***Calymene Blumenbachii*** may occasionally be found. Of the brachiopods the most abundant forms in this zone are ***Rhynchonella nucula***, ***Chonetes striatella***, ***Discina rugata***, and ***Lingula cornea***. The most characteristic lamellibranchs are ***Orthonota amygdalina***, ***Goniophora cymbæformis***, ***Pterinea lineata***, ***P. retroflexa***; some of the commonest gasteropods are ***Murchisonia corallii***, ***Platyschisma helicites***, and ***Holopella obsoleta***. The orthoceratites are specifically identical with those of the Lower Ludlow rock, and are sometimes of large size, ***Orthoceras bullatum***

being specially abundant. In all 10 genera and 14 species of fishes have been recovered from the Ludlow rocks. The fish remains consist of bones, teeth, shagreen-like scales, plates, and fin-spines. They include some plagiostomous (placoid) forms (*Thelodus*), shagreen-scales (*Sphagodus*), skin (the spines described under the name of *Onchus* being probably crustacean), and some ostracosteans (*Cephalaspis*, *Auchenaspis*, and *Pteraspis*).

In the typical Silurian region of Shropshire and the adjacent counties, nothing can be more decided than the lithological evidence for the gradual disappearance of the Silurian sea, with its crowds of graptolites, trilobites, and brachiopods, and for the gradual introduction of those geographical conditions which brought about the deposit of the Old Red Sandstone. The fine grey and olive-coloured muds, with their occasional zones of limestone, are succeeded by bright red clays, sandstones, cornstones, and conglomerates. The evidence from fossils is equally explicit. Up to the top of the Ludlow rocks the abundant Silurian fauna continues in hardly diminished numbers. But as soon as the red strata begin the organic remains rapidly die out, until at last only the fish and the large eurypterid crustaceans continue to occur.

Turning now from the interesting and extremely important though limited area in which the original type of the Upper Silurian rocks is developed, we observe that whether traced northwards or south-westwards the soft mudstones and thick limestones give way to hard slates, grits, and flagstones, among which it is scarcely possible sometimes even to discriminate what represents the Wenlock from what may be the equivalent of the Ludlow group. It is in Denbighshire and the adjacent counties that this change becomes most marked. The Tarannon shale above described passes into that region of North Wales, where it forms the base of the Upper Silurian formations. It is covered by a series of grits or sandstones which in some places are at least 3000 feet thick. These are covered by and pass laterally into hard shales, which are believed to represent parts of the true Wenlock group, perhaps even some portion of the Ludlow rocks. It is evident, however, that in spite of the wide extent over which these Silurian rocks of North Wales are spread, and the great thickness which they attain, they do not present an adequate stratigraphical equivalent for the complete succession in the original Silurian district. Instead of passing up conformably into the base of the Old Red Sandstone, as at Ludlow, they are covered by that formation unconformably. In fact they have been upturned, crumpled, faulted, and cleaved before the deposition of those portions of the Old Red Sandstone which lie upon them. These great physical changes took place in Denbighshire when, so far as the evidence goes, there was entire quiescence in the Shropshire district; yet the distance between the two areas was not more than about 60 miles. These subterranean movements were doubtless connected with those more widely extended upheavals which converted the floor of the Silurian sea into a series of isolated basins, in which the Old Red Sandstone was laid down.

In Westmoreland and Cumberland a vast mass of hard slates, grits, and flags, was identified by Sedgwick as of Upper Silurian age. These form the varied ranges of hills in the southern part of the Lake district

from near Shap to Duddon mouth. The following are the local subdivisions with the conjectural equivalents in Siluria:[1]

Hay Fell and Kirkby Moor Flags	Flaggy beds, with lamellibranchs abundant	= (?)Tilestones.
	Massive greenish and grey sandstones, with bands of fossils, *Holopella* abundant	= Upper Ludlow.
Bannisdale Slates	Calcareous beds, with *Rhynchonella navicula* abundant	= Aymestry Limestone.
	Sandstone and shale, with star-fish	= Lower Ludlow.
	Dark blue flags and grits of great thickness	= Upper Wenlock.
Coniston Grits	Flags and greywacke (*Orthoceras subundulatum*, *O. angulatum*, *Monograptus* (*Graptolithus*) *Flemingii*, *M. colonus*, *Ceratiocaris Murchisoni*), upwards of 4000 feet	= Lower Wenlock.
Coniston Flags	Dark grey coarse flags (*Cardiola interrupta*, *Orthoceras subundulatum*), 1000 feet	
Coniston Limestone (Lower Silurian)		= Caradoc or Bala.

In the northern part of the Lake district a great anticlinal fold takes place. The Skiddaw slates arch over and are succeeded by the base of the volcanic series above described. But before more than a small portion of that series has appeared the whole Silurian area is overlapped unconformably by the Carboniferous Limestone. It is necessary to cross the broad plains of Cumberland and the south of Dumfriesshire before Silurian rocks are again met with. In this intervening tract a synclinal fold must lie, for along the southern base of the uplands of the south of Scotland a belt of Upper Silurian rocks, dipping on the whole to the south-east, can be traced from the heart of the Cheviot Hills to the headlands of Wigtownshire. These rocks must reach a thickness of several thousand feet, but their top is nowhere seen. They repose on some of the older parts of the Llandeilo series, with so close a coincidence of dip and strike that no decided unconformability has yet been traced between them. They consist essentially of shales, with a considerable proportion of greywacke bands towards the base. At different horizons they contain lenticular bands of a calcareous pebbly grit. But their most characteristic feature, and one which at once distinguishes them locally from the adjoining Lower Silurian rocks, is the occurrence of a brownish black, highly fissile shale, composed of layers in most cases as thin as ordinary writing paper and usually crowded with graptolites. These peculiar bands occur throughout the whole series of rocks from bottom to top. They are sometimes so thin that 20 or 30 seams or ribs, each finely fissile, may be seen intercalated within the space of an inch of the ordinary shale or greywacke. Occasionally they form zones 80 to 100 feet thick, consisting entirely of finely leaved graptolitic shales. As a whole these Scottish Upper Silurian strata resemble lithologically the corresponding series in Westmoreland, though here and there they assume the character of mudstones not unlike those of Shropshire. The abundant fossils in them are simple graptolites (*Monograptus* (*Graptolithus*) *Sedgwickii*, *M. Becki*, *M. Flemingii*, *M. colonus*, *M. griestonensis*, *Retiolites geinitzianus*, &c.). Orthoceratites come next in point of numbers

[1] The arrangement and thicknesses here given are those in the Kendal district as mapped by Mr. Aveline and Mr. Hughes in the course of the Geological Survey (*Sheet* 98, S.E., *Explanation*, pp. 6–13, 1872).

(*Orthoceras annulatum*, *O. tenuicinctum*, &c.). In some of the shales crustacean fragments are numerous. They include large pieces of the carapace of *Dictyocaris*, with remains of *Ceratiocaris* and *Pterygotus*. The pebbly grits contain *Petraia* and crinoid stems. In the south of Kirkcudbright certain limestones and conglomerates intercalated among these shales have yielded a more varied fauna, having on the whole a decidedly Wenlock character, and including *Favosites*, *Catenipora*, *Beyrichia tuberculata*, *Phacops caudatus*, *Meristella*, *Leptæna sericea*, *Atrypa reticularis*, *Strophomena imbrex*, *Murchisonia*, *Orthoceras tenuicinctum*, &c.

It is impossible in the south of Scotland to separate the Upper Silurian rocks into Wenlock and Ludlow groups. On the whole these rocks seem to be representative mainly of the older half of the Upper Silurian divisions. They are covered unconformably by Lower Old Red Sandstone and later formations. In the counties of Edinburgh and Lanark, however, the base of the Lower Old Red Sandstone is found to graduate downward into a thick series of brown, olive, and grey shales, sandstones, and grits, containing undoubted Ludlow fossils. It is deserving of remark also that the peculiar lithological type so characteristic of the strata in the original Silurian area reappears in the centre of Scotland, many of the concretionary brown shales and olive-coloured mudstones being undistinguishable from those in the typical sections at Ludlow. Some of these beds are crowded with fossils, among the most typical of which are *Leptæna transversalis*, *Orthonota amygdalina*, *Platyschisma helicites*, *Beyrichia Klœdeni*, *Orthoceras Maclareni*, with many crustaceans of the genera *Ceratiocaris*, *Dictyocaris*, *Eurypterus*, *Pterygotus*, *Slimonia*, and *Stylonurus*. In the Pentland Hills these strata are estimated to attain a thickness of 3500 to 4000 feet, but their base is nowhere reached; in Lanarkshire they are at least as thick. Their lower portions may represent some of the higher parts of the Wenlock group.

Ireland furnishes some interesting evidence regarding the geographical changes in the west of Europe between the close of the Lower Silurian and the beginning of the Upper Silurian period. It has already been pointed out that the metamorphosed Lower Silurian rocks of the Scottish Highlands are prolonged into the north of Ireland, whence they range south-westwards to Galway Bay. In the picturesque tract between Lough Mask and the mouth of Killary harbour these metamorphosed rocks are unconformably overlaid by masses of sandstones, conglomerates, and shales more than 7000 feet thick, and containing Llandovery and Wenlock fossils with a mixture of Caradoc forms. In the midst of the greatly metamorphosed Lower Silurian platform, portions are to be found still little altered and full of fossils. The overlying Upper Silurian strata have not been metamorphosed, but contain pebbles of the altered rocks on the upturned edges of which they lie. It is evident therefore, as Mr. Hull has remarked, that the metamorphism must have occurred between the formation of the Lower and that of the Upper Silurian rocks of the region.[1] In connection with this question it should be remarked that abundant volcanic activity accompanied the deposit of these Upper Silurian rocks in the west of Ireland, successive sheets of lava (eurite) and beds of tuff forming conspicuous bands among the stratified rocks, and reaching a collective

[1] *Physical Geology of Ireland*, p. 22; Kinahan's *Geology of Ireland*, chap. iii.; *Geological Survey of Ireland*, *Explanation of Sheets* (76, 77, 83, and 84).

thickness of 800 feet and upwards. Between Brandon Head and Dingle Bay a thick mass of strata on the coast must, from the comparatively few fossils obtained from it, be held to represent Upper Silurian formations.

Scandinavia and Basin of the Baltic.[1]—The broad hollow which, running from the mouth of the English Channel across the plains of northern Germany into the heart of Russia, divides the high grounds of the north and north-west of Europe from those of the centre and south, separates the European Silurian region into two distinct areas. In the northern of these we find the Lower and Upper Silurian formations attaining an enormous development in Britain, but rapidly diminishing in thickness towards the north-east, until in the south of Scandinavia and the Gulf of Finland they reach only about $\frac{1}{25}$th of that depth. In these latter tracts, too, they have on the whole escaped so well from the dislocations, crumplings, and metamorphisms so conspicuous to the south-west, that to this day they remain over wide spaces nearly as horizontal and soft as at first. In the southern area Silurian rocks appear only here and there from amidst later formations, and almost everywhere present proofs of intense subterranean movement. Though sometimes attaining considerable thickness they are much less fossiliferous than those of the northern part of the region, except in the basin of Bohemia, where an exceedingly abundant series of Silurian organic remains has been preserved.

In the south of Scandinavia (Mjösen See, Malmö, Gothland) the Lower and Upper Silurian rocks attain a united thickness of not more than about 1200 feet, yet are said to contain representatives of all the leading subdivisions of the British series. The following table exhibits the Silurian succession in the western part of the Baltic basin with the supposed English equivalents:

Sandy beds, with *Pterinea retroflexa, Rhynchonella nucula, Orthonata retusa, Beyrichia tuberculata.* S. Gothland	= Upper Ludlow.
Upper Malmö limestone Upper Graptolite marls, *Monograptus* (*Graptolithus*) *priodon* (*Ludense*) abundant Lower Malmö limestone, with large *Orthocerata* having central siphuncles	= Lower Ludlow.
Encrinital schists with orthoceratites and *Gomphoceras pyriforme* Coral limestone (*Omphyma turbinatum* and other Wenlock corals).	= Wenlock.
Pentamerus limestone (*Pentamerus oblongus, P. galeatus, Stricklandinia lens, Leptæna transversalis, Encrinurus punctatus,* &c.) Lower argillaceous schists	= Llandovery.
Calcareous sandstones (Brachiopod schist) containing a mixture of Llandovery forms, as *Meristella angustifrons,* and many large smooth *Pentameri*. Calcareous and argillaceous flagstones (Trinucleus schist), *Orthis calligramma, O. testudinaria, O. pecten, Leptæna sericea, Conularia quadrisulcata, Asaphus expansus, Trinucleus concentricus,* &c. Chasmops limestone and Encrinital schists.	= Caradoc.

[1] Consult Angelin's "Palæontologica Suecica;" Kjerulf, "Norges Geologi," 1879 or "Geologie des Südl. Norvegen" (Gurlt), 1880.; Linnarsson, *Zeitsch. Deutsch. Geol. Gesell.* xxv. 675; *Geol. Mag.* 1876, pp. 145, 241; *Geol. Föreningens Stockholm. Förhandl.* 1877, 1879; Lundgren, *Neues Jahrb.* 1878, p. 699.

Middle Graptolite (Dicranograptus) schists, with *Phyllograptus typus*, *Didymograptus geminus*, *Diplograptus pristis*, *D. folium*, *D. teretiusculus*, and forms of *Asaphus*, *Ogygia*, *Trinucleus*, &c. . . . . Lower Orthoceratite limestone (Ceratopyge-Kalk), with *Orthoceras duplex*, *O. annulatum*, *Lituites cornu-arietis*, *Orthis calligramma*, *O. elegantula*, *Bellerophon bilobatus*, *Ptychopyge applanata*, *Megalaspis limbatum*, *Agnostus glabratus*, &c.	= Llandeilo.
Lower Graptolite (Phyllograptus) schists (with numerous graptolites of the genera *Didymograptus*, *Tetragraptus*, *Dichograptus*, *Temnograptus*, *Phyllograptus*, &c., resting on the Cambrian Alum-schists]	= Arenig in part.

In the Christiania district, according to Kjerulf, the following subdivisions can be established:

Upper.	Compact grey, often bituminous limestone, with abundant *Orthoceras cochleatum* and *Chonetes striatella*.
	Grey somewhat bituminous limestone, with shales and clays.
	Fissile green or grey marly shales containing the last graptolites. This and the two overlying members have a united depth of 835 Norwegian feet at Ringerige.
	Coral-limestone and Pentamerus limestone.
Lower.	Calcareous sandstone, with *Rhynchonella diodonta* and shales, 150 to 370 feet.
	Shales and marls, with nodules and short beds of cement-stone (*Trinucleus*, *Chasmops*), 700 feet.
	Graptolite shales, Limestone in two or more bands (Orthoceras-, Asaphus-, Megalaspis-limestone), 250 feet in places.

Though the general resemblance of the succession of fossils in Scandinavia and in Britain is singularly close, there are, as might have been anticipated, differences in the range of species, some forms having appeared earlier or having survived later in the one region than in the other. Thus the *Pentamerus oblongus* ascends in Scandinavia into rocks full of Wenlock corals, but does not occur in the Wenlock group of Britain. On the other hand, among Scandinavian strata containing such characteristically Lower Silurian genera of trilobites as *Asaphus*, *Trinucleus*, and *Ogygia*, there occur organisms which in Britain are typically Upper Silurian, such as *Orthoceras dimidiatum* and *O. distans*, two fossils of the Ludlow rocks. In Britain no graptolites have yet been found below Arenig rocks, but in Scandinavia they occur in the Dictyonema schists, which are probably of Upper Cambrian age. These facts possess considerable importance in relation to the value of palæontological evidence in correlating the formations of different countries, since they indicate that the order of succession found to hold good in one region cannot be rigidly applied to others, as is so often attempted by palæontologists, and that in such cases it is not from individual species so much as from the general facies of the fossils that we must draw geological parallels. The first appearance and duration of a species have doubtless greatly varied in different regions. It is altogether against the analogies of nature to hold that a species has everywhere had nearly or precisely the same chronological range.

In the northern regions of Sweden and Norway the Silurian formations present a remarkably different development from that just described. According to the researches of A. E. Törnebohm they are there represented by vast masses of quartzite, mica-slate, gneiss, hornblende-schist, clay-slate, and other crystalline rocks. The schists can be seen reposing upon recognizable Silurian strata in numerous natural sections, and without

crumpling, invasion of eruptive masses or other disturbance. In their general character and order of succession these Scandinavian rocks present many points of resemblance to the altered Silurian series of the Highlands of Scotland already described (p. 583). Törnebohm divides them into two series—the Seve group, composed of a set of quartzites, and crystalline schists covered by the Köli group, in which mica-schists and clay-slates are the chief rocks. The latter may be metamorphosed shales, and it is remarkable that, as in Scotland, the lower parts of the group are generally the less altered.[1]

In Russia Silurian rocks must occupy the whole vast breadth of territory between the Baltic and the flanks of the Ural Mountains, beyond which they spread eastward into Asia. Throughout most of this extensive area they lie in horizontal undisturbed beds, covered over and concealed from view by later formations. Along the flanks of the Urals they have been upheaved, and placed on end or at a high angle against the central portions of that chain, and have been partially metamorphosed into chlorite-schist, mica-schist, quartz-rock, and other crystalline masses. But along the southern margin of the Gulf of Finland they appear at the surface as soft clays, sands, and unaltered strata, which, so far as their lithological characters go, might be supposed to be of late Tertiary date, so little have they been changed during the enormous lapse of ages since Lower Palæozoic time. The great plains between the Ural chain on the east and the rising grounds of Germany on the south-west have thus from a remote geological antiquity been exempted from the terrestrial corrugations which have affected so much of the rest of Europe. They have been alternately, but gently, depressed as a sea-floor, and elevated into steppes or plains. The following subdivisions have been established by F. Schmidt among the Silurian rocks of north-west Russia :[2]

I. *Upper Silurian.*

Tile-stone.	Sandy variable limestone, with marly layers passing into sandstone (*Beyrichia tuberculata*, *Grammysia cingulata*, *Chonetes striatella* and numerous fish remains, *Onchus*, &c.).
Lud-low.	Upper Oesel Group, yellow marly and sometimes dolomitic strata (*Rhynchonella Wilsoni*, *Chonetes striatella*, *Platyschisma helicites*, *Eurypterus remipes*, and fish remains, &c.).
Wenlock.	Lower Oesel group, dolomite, with marl and coral limestone below (*Propora tubulata*, *Halysites distans*, *Beyrichia Klœdeni*, *Encrinurus punctatus*, *Proëtus concinnus*, *Meristella tumida*, *Spirifera crispa*, *Leptæna transversalis*, *Euomphalus funatus*, *Orthoceras annulatum*, &c.).
Llandovery.	Pentamerus band, with *P. ehstonus* (*oblongus*), *Alveolites Labechei*, *Bellerophon dilatatus*, *Bronteus signatus* (*laticauda*).
	Compact limestone and dolomite with siliceous nodules (*Heliolites interstinctus*, *Ptilodictya scalpellum*, *Strophomena pecten*, *Orthis hybrida*, *Pentamerus linguifer*, *Leperditia marginata*).
	Pentamerus band, limestone, and dolomite, with *Pentamerus borealis*, &c.

II. *Lower Silurian.*

Caradoc.	Borkholm limestones and marls (*Halysites labyrinthica*, *Heliolites megastoma*, *Syringophyllum*, *organum*, *Lichas margaritifer*, *Pleurorhynchus dipterus*, *Orthoceras calamiteum*, &c.).
	Lyckholm, yellow or grey compact limestone and marls (*Orthis flabellulum*, *O. Actoniæ*, *O. insularis*, &c.).
	Wesenberg limestone and marl (*Orthis testudinaria*, *Encrinurus multisegmentatus*, *Lichas Eichwaldi*, &c.).

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[1] A. E. Törnebohm, *Bihang till K. Svenska Vet. Akad. Handl.* i. No. 12, 1873.

[2] *Untersuchungen über die Silurische Formation von Ehstland, Nord Livland und Oesel*, published in *Archiv für die Naturkunde Liv. Ehst. und Kurlands*, Dorpat, 1858.

Llandeilo.	Limestone usually somewhat bituminous, with partings of reddish-yellow and brown very bituminous marl (*Beyrichia complicata*, *Asaphus acuminatus*, *Orthis calligramma*, *Leptæna sericea*, &c.).
	Orthoceratite limestone (Vaginaten-Kalk) and marl bands, 15 to 40 feet thick (*Monticulipora petropolitana*, *Echinosphærites aurantium*, *Asaphus expansus*, *Orthis calligramma*, *Orthoceras vaginatum*, &c.).
	Limestone, full of glauconite grains, especially towards the bottom (*Orthis calligramma*, *O. extensa*, abundant fragments of *Illænus* and *Asaphus*, &c.).
Arenig.	Glauconite sand (6 feet), with numerous foraminifera in the glauconite grains (*Panderella*, *Cymbulia*, *Tiedemannia*, &c.) and the "Conodonts" of Pander.
	Alum-slate (10 feet), highly carbonaceous, with pyrite-nodules and abundant graptolites (*Dictyonema Hisingeri*, *Obolus*, &c.).
	Ungulite sandstone (120 feet), yellow to white, with (in the upper part) abundant shells of *Obolus Apollinis* ("Ungulites" of Pander).
	Blue Clay, with sandstone bands, sparingly fossiliferous; bored at Revel to a depth of 800 feet without its bottom being reached.

Bohemia.[1]—In the centre and south of Europe by far the most important Silurian area is the basin of Bohemia, so admirably worked out by M. Barrande, wherein the formations are grouped as in the subjoined table:

Upper Silurian.	3rd Fauna.	Étage H	Shales with coaly layers and beds of quartzite (*Phacops fecundus*, *Tentaculites elegans*), with species of *Leptæna*, *Orthoceras*, *Lituites*, *Goniatites*, &c.	850 ft.
		„ G	Argillaceous limestones with chert, shales, and calcareous nodules . . . . Numerous trilobites of the genera *Dalmanites*, *Bronteus*, *Phacops*, *Proëtus*, *Harpes*, and *Calymene*; *Atrypa reticularis*, *Pentamerus linguifer*.	1000 „
		„ F	Pale and dark limestone with chert. *Harpes*, *Lichas*, *Phacops*, *Atrypa reticularis*, *Pentamerus galeatus*, *Favosites gothlandica*, *F. fibrosa*, *Tentaculites*.	
		„ E	Shales with calcareous nodules, and shales resting on sheets of igneous rock (300 ft.) . . A very rich Upper Silurian fauna, abundant cephalopods, trilobites, &c.; *Halysites catenularia*, graptolites in many species.	450–900 „
Lower Silurian.	2nd Fauna.	„ D	Yellow, grey, and black shales, with quartzite and conglomerate at base. . . . . Abundant trilobites of genera *Trinucleus*, *Ogygia*, *Asaphus*, *Illænus*, *Remopleurides*, &c.	3000 „
Cambrian.	Primordial Fauna.	„ C	Shales or "schists," sometimes with porphyries and conglomerates . . . . . . *Paradoxides*, *Ellipsocephalus*, *Agnostus*, and other genera of trilobites referred to above (*ante*, p. 659).	900–1200 „
Azoic.		„ B „ A	Schists wholly unfossiliferous resting on gneiss.	

The lower two *étages* (A, B) correspond probably to some of the older parts of the British Cambrian series, and perhaps in part to still older rocks. Étage C, or the Primordial Zone, is the equivalent of the Upper Cambrian rocks of Wales, possibly also partly of the Arenig series. Étage D, subdivided into five groups (*d*1, *d*2, *d*3, *d*4, and *d*5), appears to be, on the whole, representative of the Lower Silurian formations of the British area, though it is impossible to make the minor subdivisions in

[1] See Barrande's magnificent work, "Système Silurien de la Bohème."

the two countries agree. The remaining four étages answer to the English and Welsh Upper Silurian groups—the highest stage of all (H) indicating by its organic remains the approach of the Devonian system.

Small though the area of the Silurian basin of Bohemia is (for it measures only 100 miles in extreme length by 44 miles in its greatest breadth), it has proved extraordinarily rich in organic remains. M. Barrande has named and described several thousand species from that basin alone, the greater number being peculiar to it. Some aspects of its organic facies are truly remarkable. One of these is the extraordinary variety and abundance of its straight and curved cephalopods. M. Barrande has determined 18 genera and two subgenera, comprising in all no fewer than 1127 distinct species. The genus *Orthoceras* alone contains 554 species, and *Cyrtoceras* has 330.[1] Of the trilobites, which appear in great numbers and in every stage of growth, the same indefatigable explorer has detected as many as 42 distinct genera, comprising 350 species; the most prolific genus being *Bronteus*, which includes 46 species entirely confined to the *3rd* fauna or Upper Silurian. *Acidaspis* has 40 species, of which six occur in the *2nd* and 34 in the *3rd* fauna. *Proëtus* also numbers 40 species, which all belong to the *3rd* fauna, save two found in the *2nd*. Other less prolific but still abundant genera are *Dalmanites*, *Phacops*, and *Illænus*. The *2nd* fauna, or Lower Silurian series, contains in all 32 genera and 127 species of trilobites, while the *3rd* fauna, or Upper Silurian series, contains 17 genera and 205 species, so that generic types are more abundant in the earlier and specific varieties in the later rocks.[2]

France and Belgium.—The researches principally of Gosselet have demonstrated that a considerable part of the strata grouped by Dumont in his "terrain rhénan," and generally supposed to be of Devonian age, must be relegated to the Lower Silurian series. He shows that, though almost concealed by younger formations, the Silurian rocks that are laid bare at the bottom of the valleys of Brabant can be paralleled in a general way as under:

Caradoc.	*Schistes de Fosse;* psammites and lustrous shales with nodules and even beds of limestone, containing most of the fossils of the group below, with the addition of *Sphærexochus mirus*, and *Halysites catenularia*.
	Schistes de Gembloux; pyritous black and greenish shales, which at Grand-Manil, in the valley of the Orneau, have yielded upwards of 50 species of fossils, including *Calymene incerta, Trinucleus setiformis, Illænus Bowmanni, Bellerophon bilobatus, Strophomena rhomboidalis, Orthis testudinaria, O. vespertilio, O. calligramma, O. Actoniæ, Graptolithus priodon, Climacograptus scalaris.*
Llandeilo.	*Schistes bigarrés d'Oisquerq;* variegated flagstones and shales, sometimes black and graphitic.
	Schistes aimantifères de Tubize; green, sometimes bluish and blackish rocks, comprising shales with magnetite and pyrite, and shales passing into slate and into quartzite.
	Quartzites de Blammont; whitish and greenish quartzites becoming pink by weathering.[3]

The Silurian rocks of Belgium comprise several contemporaneously erupted masses of porphyrite and of diabase, as well as beds of porphyroid, arkose, and eurite.

Silurian rocks have been detected in many parts of the old Palæozoic

[1] *Syst. Silur.* ii. suppt. p. 266, 1877.
[2] *Op. cit.* i. suppt. "Trilobites," 1871.
[3] Gosselet, "Esquisse Géologique du Nord de la France," p. 34. Mourlon, "Géol. de la Belgique," p. 40. Malaise, "Mém. Couronn. Acad. Roy. Belgique," 1873.

ridge of the north-west of France. According to recent researches,[1] the order of succession in Brittany (Ille-et-Vilaine) is as under:

White limestone of Erbray (*Calymene Blumenbachii*, *Harpes venulosus*).
Ampelitic or carbonaceous limestone of Briasse.
Sandy and ferruginous nodules of Martigné-Ferchaud, Thourie, &c. (*Cardiola interrupta*, *Monograptus* (*Graptolithus*) *priodon*).
Carbonaceous (ampelitic) shales of Poligné, and phthanites of Anjou (*Monograptus* (*Graptolithus*) *colonus*).
Slates of Riadan (*Trinucleus*).
Sandstones (May, Thourie, Bas Pont, Saint-Germain de la Bouexière, &c.), containing *Trinucleus Goldfussi*, *Calymene Bayani*, *Orthis redux*, *O. budleighensis*, *O. pulvinata*, *O. valpyana*, *O. Berthosi*, *Nucleospira Vicaryi*, *Lingula Morierei*, *Pseudarca typa*, *Diplograpsus Baylei*; probably equivalent to the British Caradoc group.
Slates of La Couyère (*Orthis Berthosi*).
Nodular shales of Guichen, &c. (*Calymene Tristani*, *Placoparia Tourneminei*, *Acidaspis Buchii*).
Slates of Angers (*Ogygia Desmaresti*).
Shales of Laillé and Sion (*Placoparia Zippei*, *Hyolithes cinctus*).
Armorican sandstone (Grès Armoricain), possibly the base of the Lower Silurian (lowest Llandeilo or Arenig) or second fauna of Barrande (*Asaphus armoricanus*, *Lingula Lesueuri*, *L. Hawkei*, *L. Salteri*, *Dinobolus Brimonti*, *Lyrodesma armoricana*, annelides).
Red shales and conglomerates without fossils.

In Germany Silurian rocks appear in a few detached areas, but present a great contrast to those of Bohemia in their comparatively unfossiliferous character, and the absence of any one continuous succession of the whole Silurian system. They occur in the Thuringer Wald, where a series of fucoidal-schists (perhaps Cambrian) passes up into slates, greywackes, &c., with *Lingula*, *Discina*, *Calymene*, numerous graptolites, and other fossils. These strata (from 1600 to 2000 feet thick) may represent the Lower Silurian groups. They are covered by some graptolitic alum-slates (*Monograptus*, *Diplograptus*), shales, flinty slates, and limestones (*Favosites gothlandica*, *Cardiola interrupta*, *Tentaculites acuarius*, &c.), which no doubt represent the Upper Silurian groups, and pass into the base of the Devonian system.[2] Among the Harz Mountains certain greywackes and shales containing land-plants (lycopods, &c.), trilobites (*Dalmanites*, &c.), graptolites, &c., are regarded as of intermediate age between true Upper Silurian and Lower Devonian rocks.[3] In the western half of the Spanish peninsula Silurian rocks are found flanking the older schists and crystalline masses, and spreading over a vast area of the table-land. They appear to belong chiefly if not wholly to the lower division of the system, and they include representatives of Barrande's primordial zone, containing 19 species of organisms of which nine are primordial trilobites.

Among the Alps the band of ancient sedimentary rocks which, flanking the crystalline masses of the central chain, has been termed the "greywacke zone," has in recent years been ascertained to contain representatives of the Silurian, Devonian, Carboniferous, and Permian systems. In the eastern Alps a belt of clay-slate and greywacke, with limestone, dolomite, magnesite, ankerite, and siderite runs from Kitzbühel

[1] De Tromelin et Lebesconte, *Bull. Soc. Géol. France*, 1876, p. 585. *Assoc. Franç* 1875. *Bull. Soc. Linn. Normandie*, 1877, p. 5. See also Dalimier, "Stratigraphie des Terrains primaires dans la presqu'île de Cotentin," Paris, 1861; *Bull. Soc. Géol. France*, 1862, p. 907; De Lapparent, *Bull. Soc. Géol. France*, 1877, p. 569.
[2] Richter, *Zeitsch. Deutsch. Geol. Gesell.* xxi. p. 359; xxvii. p. 261.
[3] Lossen, *op. cit.* xx. p. 216; xxi. p. 284; xxix. 612.

in the Tyrol as far as the south end of the Vienna basin. A few orthoceratites, brachiopods, and other fossils found in this belt are regarded as Upper Silurian forms. Remains of corals, crinoids, and brachiopods have been met with even deep beneath the limit formerly drawn between the Palæozoic and Archæan rocks of the Alps, so that there is now reason to believe that a considerable part of the crystalline schists may be altered Palæozoic rocks. Silurian rocks containing graptolites have also been met with among the southern slopes of the Alps in Carinthia.[1]

North America.[2]—In the United States and Canada Silurian rocks spread continuously over a vast territory, from the mouth of the St. Lawrence south-westwards into Alabama and westwards by the great lakes. They almost encircle and certainly underlie all the later Palæozoic deposits of the great interior basin. The rocks are most typically developed in the State of New York, where they have been arranged as in the subjoined table:

B. Upper Silurian.

IV. Oriskany Formation.	Oriskany sandstone (*Spirifera arenosa*)	Ludlow.
III. Lower Helderberg Formation.	(4) Upper Pentamerus limestone (*Pentamerus pseudogaleatus*) . . . . (3) Delthyris limestone (*Meristella lævis*). . . (2) Lower Pentamerus limestone (*Pentamerus galeatus*) (1) Water-lime (*Tentaculites*, *Eurypterus*, and *Pterygotus*)	Ludlow.
II. Salina Formation.	Onondago salt group, consisting of red and grey marls, sandstones and gypsum, with large impregnation of common salt, but nearly barren of fossils . .	Ludlow.
I. Niagara Formation.	(3) Niagara shale and limestone (*Halysites*, *Favosites*, *Calymene Blumenbachii*, *Homalonotus delphinocephalus*, *Leptæna transversalis*, &c.) . . .	Wenlock.
	(2) Clinton group (*Pentamerus oblongus*, *Atrypa reticularis*, &c.) . . . . (1) Medina group with Oneida conglomerate (*Modiolopsis orthonota*)	Upper Llandovery.

A. Lower Silurian.

II. Trenton Formation.	(3) Cincinnati (Hudson River) group (*Syringopora*, *Halysites*, *Diplograptus pristis*, *Pterinea demissa*, *Leptæna sericea*).		
	(2) Utica group—Utica shale.		
	(1) Trenton group.	Trenton limestone. Black River limestone. Birdseye limestone.	*Graptolithus amplexicaulis*, *Trinucleus concentricus*, *Orthis testudinaria*, *Murchisonia*, *Conularia*, *Orthoceras*, *Cyrtoceras*, &c.
I. Canadian Formation.	(3) Chazy group—Chazy limestone (*Maclurea magna*, *M. Logani*, *Orthoceras*, *Illænus*, *Asaphus*).		
	(2) Quebec group (upwards of 100 species of trilobites of genera *Agnostus*, *Ampyx*, *Amphion*, *Conocoryphe*, *Dikelocephalus*, *Illænus*, *Asaphus*, &c., more than 50 species of graptolites).		
	(1) Calciferous group (graptolites, *Lingulella acuminata*, *Leptæna*, *Conocardium*, *Ophileta compacta*, *Orthoceras primigenium*, 14 species of trilobites of the genera *Amphion*, *Bathyurus*, *Asaphus*, *Conocoryphe*).		
	Potsdam formation, representing Cambrian (see *ante*, p. 660).		

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[1] Von Hauer, "Geologie," p. 216. Stache, *Jahrb. Geol. Reichsanstalt.* xxiii. p. 175; xxiv. 136. The latter memoir contains a detailed description of the greywacke zones of the eastern Alps, which the author divides into five pre-triassic groups: 1. Quartzphyllite group; 2. Kalkphyllite group; 3. Kalkthonphyllite group; 4. Group of the older greywackes (Silurian and Devonian); 5. Group of the Upper Coal and Permian rocks.

[2] See especially the *Memoirs of the Geological Survey of Canada* and the numerous monographs of Prof. James Hall, of Albany.

It is interesting to observe the number of genera and even of species common to the Silurian rocks of America and Europe, and the close parallelism in their order of appearance. Not a few of the widely diffused forms occur in Arctic America, so that a former migration along shallow northern waters between the two continents is rendered highly probable. Among these common species the following may be enumerated as occurring in the Upper Silurian rocks of New York, the coasts of Barrow Straits within the Arctic Circle, Britain, and the Baltic basin:—*Stromatopora concentrica, Halysites catenularia, Favosites gothlandica, Orthis elegantula, Atrypa reticularis.* The graptolites appear to have reached their full development and to have waned at corresponding stages of the Silurian period on each side of the Atlantic. Among the crustacea trilobites were the dominant order, represented in each region by a similar succession of genera, and even to some extent of species. And as these earlier forms of articulates waned there appeared among them about the same epoch in the geological series the eurypterids of the Water Lime of New York and of the Ludlow rocks of Shropshire and Lanarkshire.

Asia, &c.—Silurian rocks have been recognized over a large part of the surface of the globe. They have been found, for example, running through the Cordilleras of South America on the one hand, and among the older rocks of the Himalaya chain on the other. The Salt Range of the Punjaub contains thick masses of bright red marl with beds of rock-salt and gypsum, over which lie purple sandstones and shales containing traces of fucoids and annelids and a small brachiopod resembling *Obolus*. These saliferous rocks are probably at least as old as the Silurian period, if not older. In the regions of the Northern Punjaub and Kashmere traces of Silurian organic remains have been discovered; while in the north of Kumaun these fossils have been found in considerable quantities.

In Australia the existence of the Silurian system has been proved by the discovery of a considerable number of characteristic fossils, among which are numerous graptolites of the genera *Climacograptus, Cœnograptus, Dichograptus, Dicranograptus, Didymograptus, Diplograptus, Monograptus, Loganograptus, Phyllograptus, Retiolites,* and *Tetragraptus*, which occur in the Lower Silurian series of Victoria; also many Upper Silurian fossils from New South Wales, including such world-wide species as *Favosites gothlandica, Heliolites interstinctus, Calymene Blumenbachii, Encrinurus punctatus, Entomis tuberosa, Phacops caudatus, Atrypa reticularis, Leptæna sericea, Pentamerus Knightii, P. oblongus, Rhynchonella Wilsoni, Orthonota amygdalina, Orthoceras bullatum.*

Section III.—Devonian and Old Red Sandstone.

In Wales and the adjoining counties of England, where the typical development of the Silurian system was worked out by Murchison, the abundant Silurian marine fauna comes to an abrupt close at the base of the red rocks that overlie the Ludlow group. From that horizon upwards in the geological series we have to pass through some 10,000 feet or more of barren red sandstones and marls, until we again encounter a copious marine fauna in the Carboniferous Limestone. It is evident that between the disappearance of the Silurian and the arrival of the Carboniferous fauna very great geographical changes occurred over the site of

Wales and the west of England. For a prolonged period the sea must have been excluded, or at least must have been rendered unfit for the existence and development of marine life, over the area in question. The striking contrast in general facies between the organisms in the Silurian and those in the Carboniferous system proves how long the interval between them must have been.

The geological records of this interval are still only partially unravelled and interpreted. At present the general belief among geologists is that, while in the west and north-west of Europe the Silurian sea-bed was upraised into land in such a way as to enclose large inland basins, in the centre and south-west the geographical changes did not suffice to exclude the sea, which continued to cover that region more or less completely. In the isolated basins of the north-west a peculiar type of deposits termed the Old Red Sandstone is believed to have accumulated, while in the shallow seas to the south and east a series of marine sediments and limestones was formed to which the name of Devonian has been given. It is thus supposed that the Old Red Sandstone and Devonian rocks represent different geographical areas, with different phases of sedimentation and of life, during the long lapse of time between the Silurian and Carboniferous periods.

That the Old Red Sandstone, at least, does represent this prolonged interval can be demonstrated by innumerable sections in Britain, where its lowest strata are found graduating downward into the top of the Ludlow group, and its highest beds are seen to pass up into the base of the Carboniferous system. But the evidence is not everywhere so clear in regard to the true position of the Devonian rocks. That these rocks lie between Silurian and Carboniferous formations was long ago shown by Lonsdale to be proved by their fossils. But it is a curious fact that where the Lower Devonian beds are best developed the Upper Silurian formations are scarcely to be recognized, or, if they occur, can hardly be separated from the so-called Devonian rocks. It is therefore quite possible that the lower portions of what has been termed the Devonian series may in certain regions to some extent represent what are elsewhere recognized as undoubted Ludlow or even perhaps Wenlock rocks. We cannot suppose that the rich Silurian fauna died out abruptly at the close of the Ludlow epoch. We should be prepared for the discovery of Silurian rocks younger than the latest of those in Britain, such as M. Barrande has shown to exist in his Étage H (p. 689). The rocks termed Lower Devonian may partly represent some of these later phases of Silurian life, if they do not also mark peculiar geographical conditions of a still older period in Upper Silurian time. On the other hand, the upper parts of the Devonian system might in several respects be claimed as fairly belonging to the Carboniferous system above.

The late Mr. Jukes proposed a solution of the Devonian problem, the effect of which would be to turn the whole of the Devonian rocks into Lower Carboniferous, and to place them above the Old

Red Sandstone, which would thus become the sole representative in Europe of the interval between Silurian and Carboniferous time.[1] In the following descriptions an account will first be given of the Devonian type and then of the Old Red Sandstone.

I. DEVONIAN TYPE.

§ 1. General Characters.

ROCKS.—Throughout Central and Western Europe the Devonian system presents a remarkable persistence of petrographical characters, indicating probably the prevalence of the same kind of physical conditions over the area during the period when the rocks were accumulated. The lower division consists mainly of sandstones, grits, and greywackes. These rocks attain a great development on the Rhine, where they form the material through which the picturesque gorges of the river have been eroded. In the central zone limestones predominate, some of them crowded with the corals and molluscs of the clearer water in which they were laid down. The upper series is more variable: being in some tracts composed of sandstones and shales, in others of shales and limestones, but everywhere presenting a more shaly thin-bedded aspect than the subdivisions beneath it. Considerable masses of diabase, tuff, and other associated rocks are intercalated in the Devonian system of Germany. As a rule the rocks have been subjected to more or less disturbance, having been thrown into plications, and sometimes, as in Cornwall and Devon, having even undergone extensive cleavage. In some localities also they have been metamorphosed into schists, quartzites, &c., and have been invaded by large masses of granite and other eruptive rocks.

Among the economic products the most important in Europe are the ores of iron, lead, tin, copper, &c., which occur in veins or lenticular masses through the Devonian rocks (Devon and Cornwall, Harz, &c.). In North America the Devonian rocks of Pennsylvania contain bands of "sand-rock" charged with petroleum.

LIFE.—An abundant cryptogamic flora covered the land during the ages that succeeded the Silurian period. As the remains of this vegetation are chiefly preserved in the Old Red Sandstone facies of deposits, it is described at p. 706. The fauna of the Devonian rocks is unequivocally marine. Among the more lowly forms of life are some the true zoological grade of which has been the subject of much uncertainty. Of these, the fossil known as *Calceola sandalina* (Fig. 330) has been successively described as a lamellibranch, a

[1] See his papers in *Journ. Roy. Geol. Soc. Ireland* (1865), i. pt. 1, new ser., and *Quart. Journ. Geol. Soc.* xxii. (1866), and his pamphlet on *Additional Notes on Rocks of North Devon*, &c., 1867. The "Devonian question," as it has been called, has evoked a large number of papers, of which, besides those quoted in subsequent pages, the following may be enumerated:—Prof. Hull, *Q. J. Geol. Soc.* xxxv. (1879), p. 699; xxxvi. (1880), p. 255. A. Champernowne, *Geol. Mag.* v. 2nd Ser. (1878), p. 193; vi. (1879), p. 125; viii. (1881), p. 410. The general verdict has been adverse to the explanation of the structure of North Devon proposed by Mr. Jukes.

hippurite, and a brachiopod; but is now regarded as a rugose coral possessing an opercular lid. The *Pleurodictyum problematicum*, a well-known form of the Lower Devonian beds, is now classed with the *Favositidæ* among the perforate corals. Numerous forms of the puzzling genus *Stromatopora* occur in some of the limestones; and the curious *Receptaculites*, already (p. 663) referred to, is a well-known Devonian fossil. The corals of the Devonian seas were both abundant in individuals and varied in their specific and generic range. Not a single species is common either to the Silurian system below or the Carboniferous above. Among the rugose forms the genera *Cyathophyllum, Acervularia,* and *Cystiphyllum* are characteristic. The tabulate kinds belonged chiefly to the two important genera of *Favosites* and *Alveolites*. Of the echinoderms by far the most abundant representatives are crinoids, which occur in great profusion in the limestones, sometimes forming entire beds of rock. They belong chiefly to the two families of *Cyathocrinidæ*, simple pedunculate forms with five branching arms, and the *Cupressocrinidæ*, having five arms which when folded up form a pentagonal pyramid the accurate fitting of which recalls the ambulacra of sea-urchins. The Cystideans appear to have died out in the Devonian period. True star-fishes also occur (*Helianthaster, Astropecten, Cœlaster*).

The known crustacean fauna of the Devonian period indicates a striking diminution both in number of individuals and of species of trilobites (Fig. 329). Most of the genera so abundant and characteristic among the Silurian rocks are now absent, the most frequent Devonian forms being species of *Phacops, Homalonotus, Dalmanites,* and *Bronteus*. The ostracods are chiefly represented by the genus *Entomis* (*Cypridina*), which occurs in enormous numbers in some Upper Devonian shales ("Cypridinen-schiefer"). The phyllopods and eurypterids occur chiefly in the Old Red Sandstone, and are noticed on p. 710 (Fig. 329, *d*). Altogether 45 genera and 290 species of Devonian crustacea are known.

Among the mollusca of the Devonian rocks remains of the pteropod *Tentaculites* are not uncommon. The brachiopods now reached perhaps their maximum development, whether as regards individual abundance or number of specific and generic forms; no fewer than 61 genera and 1100 species having been described. They compose three-fourths of the known Devonian fauna. While all the families of the class are represented, the most abundant are the *Spiriferidæ*, including the genera *Spirifera, Cyrtia, Athyris* (*Spirigera*), *Uncites*, and *Atrypa*, and the *Rhynchonellidæ, Rhynchonella, Camarophoria*, and *Pentamerus*. The Strophomenids or Orthids, so abundant in the Silurian rocks, are now represented by a waning number of forms, including the genera *Orthis, Strophomena, Streptorhynchus,* and *Leptæna*. The Productids made their appearance in Silurian times, but were more abundant in the Devonian seas, where their most frequent genera were *Chonetes* and *Productus*, both of which attained their maximum development in the Carboniferous period. One of the most characteristic and largest Devonian

brachiopods is *Stringocephalus*—a genus allied to *Terebratula*, but entirely confined to this geological system (Fig. 330). Another characteristic terebratula-like form is *Rensseleria*.

The known Devonian lamellibranchs number 90 genera and 900 species, belonging chiefly to the genera *Pterinea, Cardiola, Megalodon,*

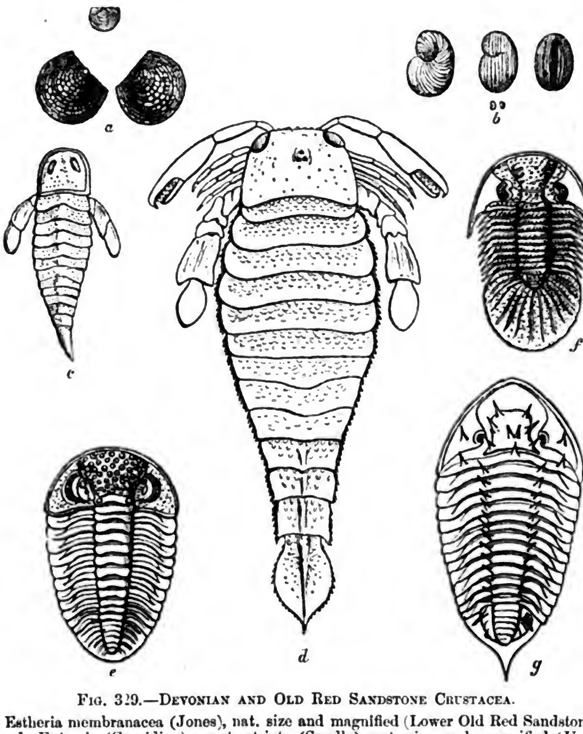


FIG. 329.—DEVONIAN AND OLD RED SANDSTONE CRUSTACEA.

a, Estheria membranacea (Jones), nat. size and magnified (Lower Old Red Sandstone); *b*, Entomis (Cypridina) serrato-striata (Sandb.), nat. size and magnified (Upper Devonian); *c*, Eurypterus pygmæus (Salt.) (Lower Old Red Sandstone); *d*, Pterygotus anglicus (Ag.) (Lower Old Red Sandstone); *e*, Phacops latifrons (Bronn) (Lower Devonian); *f*, Bronteus flabellifer (Goldf.) (Lower Devonian); *g*, Homalonotus armatus (Burm.) (Lower Devonian).

Grammysia, Cucullæa, Curtonotus, Lucina, and *Aviculopecten; Pterinea* being specially abundant in the lower, *Cucullæa* and *Curtonotus* in the upper subdivision of the system. The most important genera of gasteropods are *Euomphalus, Murchisonia. Loxonema, Macrocheilus,* and *Pleurotomaria,* with the heteropods *Bellerophon* and *Porcellia.*

The cephalopods embrace representatives of both the tetrabranchiate families of Nautilids and Ammonitids. Among the Nautilids are the genera *Clymenia* (50 species), an especially abundant form in some of the Upper Devonian shales and limestones, *Gyroceras*, *Orthoceras* (130 species), *Cyrtoceras* (60 species), and *Gomphoceras*. The great family of the Ammonites had in the Devonian waters representatives of the more abundant coiled forms in the character-

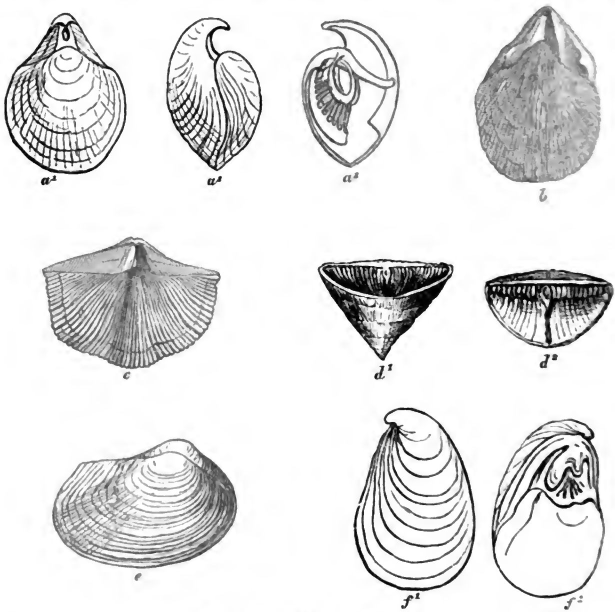


Fig. 330.—Devonian Fossils.

a^1, Stringocephalus Burtini (Def.); a^2, Do. lateral, and a^3, Do. internal view; *b*, Uncites gryphus (Def.); *c*, Spirifera disjuncta (Sow.); *d*, Calceola sandalina (Linn.); d^2, Opercular lid of do.; *e*, Cucullæa Hardingii (Sow.); *f*, Megalodon cucullatus (Sow.).

istic genus *Goniatites* (168 species), and of the straight forms in *Bactrites* (9 species). In the Devonian rocks of Central Europe scanty remains of the great fish fauna of the Old Red Sandstone have been found, more especially in the Eifel, but seldom in such a state of preservation as to warrant their being assigned to any definite place in the zoological scale. Recently, E. Beyrich has described from Gerolstein in the Eifel an undoubted species of *Pterichthys*, which, as it cannot be certainly identified with any known form, he names *P. Rhenanus*. A *Coccosteus* has been

described by F. A. Roemer from the Harz, and more recently one has been cited from Bicken near Herborn by Von Koenen; but, as Beyrich points out, there may be some doubt as to whether the latter is not a *Pterichthys.*[1] A *Ctenacanthus,* seemingly undistinguishable from the *C. Bohemicus* of Barrande's Étage G, has also been obtained from the Lower Devonian "Nereitenschichten" of Thuringia.[2] Two sharks (*Palædaphus devoniensis* and *Byssacanthus Gosseleti*) have been obtained from the Belgian and north of France area. The characteristic *Holoptychius nobilissimus* has recently been detected in the Psammite de Condroz, which in Belgium forms a characteristic sandy portion of the Upper Devonian rocks. These are interesting facts, as helping to link the Devonian and Old Red Sandstone types together. But they are as yet too few and unsupported to warrant any large deduction as to stratigraphical correlations between these types. The fishes of the Old Red Sandstone are noticed on p. 710.

§ 2. Local Development.

Britain.[3]—The name "Devonian" was first applied by Sedgwick and Murchison to the rocks of North and South Devon and Cornwall, whence a suite of fossils was obtained which Lonsdale pronounced to be intermediate in character between Silurian and Carboniferous. The actual passage of these strata into Silurian rocks cannot be determined from any section, but they clearly graduate upward into Carboniferous strata. They have been arranged into three divisions, as in the subjoined table:

UPPER	Pilton and Pickwell-Down Group.—Grey slate with courses of impure limestone (Pilton) passing down into yellow, brown, and red sandstones (Baggy Point, Marwood), and a series of hard grey and red sandstones and micaceous flagstones at the base (Pickwell-Down, Dulverton, Morte Bay).
MIDDLE	Ilfracombe Group.—Grey unfossiliferous slates (Morte Hoe, Woolacombe, and Lee Bay) passing down into calcareous fossiliferous slates and limestones (Ilfracombe, Combe Martin, Torquay, Plymouth), resting on hard green, grey, and red grits, sandstones, and conglomerates (Hangman Hill).
LOWER	Lynton Group.—Soft slates with thin limestone and sandstone bands (Lynton), resting on lowest schists and red grey micaceous sandstones (Lynton, Lynmouth, Foreland, &c.). Base not seen.

The total thickness of these rocks is given by Dr. Haughton at 9600 feet. Their enclosed fauna numbers about 400 species, chiefly found in the middle group.

LOWER.—The clay-slate of Looe, Cornwall, has yielded a species of *Pteraspis,* also *Pleurodictyum problematicum.* The lower gritty slates and limestone bands of North Devon contain, among other fossils, *Favosites cervicornis, Cyathophyllum helianthoides, Petraia celtica, Pleurodictyum problematicum, Cyathocrinus* (two species), *Homalonotus* (two species), *Phacops laciniatus, Fenestella antiqua, Atrypa reticularis, Orthis arenata, Spirifera canalifera, S. lævicosta, Pterinea spinosa,* &c.

The British Lower Devonian rocks appear as yet to have supplied no

[1] *Zeitsch. Deutsch. Geol. Gesell.* xxix. 751. [2] *Op. cit.* 423.

[3] Sedgwick and Murchison, *Trans. Geol. Soc.* 2nd ser. v. p. 633. Lonsdale, *Proc. Geol. Soc.* iii. p. 281. Etheridge, *Q. J. Geol. Soc.* xxiii. (1867), 568, where a copious bibliography up to date will be found; also *Op. cit.* xxxvii., Address, p. 178.

gasteropod nor cephalopod and only 21 species of brachiopods. Traces of fish remains have been obtained among them in the form of bones and coprolitic débris. So far as observation has gone, not a single Silurian species has been certainly detected in the Devonian rocks of Britain, with, according to Mr. Etheridge, the sole exception of the long-lived and universally diffused *Atrypa reticularis*. There can be no doubt, however, from the meagre list of fossils from the Lower Devonian rocks of Devon and Cornwall, that either the conditions for the existence or those for the fossilization of the early Devonian fauna must have been singularly unfavourable in the south-west of England. It would be rash to argue as to the extinction of the Silurian fauna from the unsatisfactory evidence of these rocks.

Middle.—As above remarked, this is the great storehouse of Devonian fossils in the south-west of England. In this fauna, as tabulated by Mr. Etheridge, there are 8 protozoa, including 5 species of *Stromatopora*, of which *S. concentrica* and *S. placenta* are characteristic; 24 genera and 4? species of actinozoa, among which the corals *Acervularia* (7 species), *Alveolites* (4), *Cyathophyllum* (12), *Favosites*, *Pleurodictyum*, and *Petraia* are conspicuous; 6 genera and 12 species of crinoids (*Hexacrinus*, *Cyathocrinus*, *Cupressocrinus*, &c.); a pteropod (*Tentaculites annulatus*); 5 genera and 6 species of crustaceans, which are all trilobites (*Phacops granulatus*, *P. latifrons*, *P. punctatus*, *Bronteus flabellifer*, *Cheirurus articulatus*, *Harpes macrocephalus*). The bryozoa are represented by 6 genera and 7 species. The brachiopods are the most abundant forms, numbering at present 23 genera and 80 species out of a total British Devonian list of 26 genera and 116 species. Among them are *Athyris concentrica*, *A. lachryma*, *Atrypa reticularis*, *A. desquamata*, *Camarophoria rhomboidea*, *Cyrtina Lemarlii*, *Orthis striatula*, *Rhynchonella acuminata*, *R. pugnus*, *Pentamerus brevirostris*, *Spirifera Verneuili* (*disjuncta*), *Stringocephalus Burtini*, *Uncites gryphus*, &c. The lamellibranchs are poorly represented, 13 genera only occurring, many of them represented by only one species; the most common genera being *Pterinea*, *Aviculopecten*, and *Megalodon*. The gasteropods are likewise present in but small numbers and variety; 12 genera and 36 species have been enumerated. Of these species, 5 (*Acroculia vetusta*, *Loxonema rugiferum*, *L. tumidum*, *Murchisonia angulata*, and *M. spinosa*) survived into the Carboniferous period. The cephalopods are represented by 5 genera, the most abundant specifically being *Cyrtoceras* (12 species), *Orthoceras* (8), and *Goniatites* (12); one species of *Nautilus* also occurs. Of the total list of fossils a large proportion is found in the Middle Devonian rocks of the continent of Europe.

Upper.—From the calcareous portions of the Petherwin and Pilton beds of Cornwall and Devon a considerable number of fossils has been obtained. Among the more characteristic of these we find 11 species of the coiled cephalopod *Clymenia* (*C. undulata*, *C. lævigata*, *C. striata*), a number of species of *Goniatites* (*G. intumescens*, *G. multilobatus*, *G. retrorsus*, *G. auris*), *Bactrites Schlotheimi*, the trilobites *Phacops granulatus* and *P. latifrons*, the small ostracod *Entomis* (*Cypridina*) *serrato-striata*, the brachiopods *Spirifera Verneuili* or *disjuncta*, *Strophomena rhomboidalis*, *Chonetes hardrensis*, *Productus subaculeatus*, and the lamellibranch *Cucullæa Hardingii*. Some traces of fishes, referred to *Coccosteus*, have been recently found. The Marwood and Baggy Point beds have also yielded traces of land plants, such as *Knorria dichotoma* and *Palæopteris Hibernica*, the latter fern being common in some parts of the Upper Old Red Sandstone of Ireland.

The higher red and yellow sandy portions of the Upper Devonian rocks shade up insensibly at Barnstaple in North Devon into strata which by their fossils are placed at the base of the Carboniferous Limestone series. But in no other locality save these south-western districts can such a passage be observed. In all other places the Carboniferous system, where its true base can be seen, passes down into the red sandy and marly strata of the Upper Old Red Sandstone without marine fossils. Of the total known Devonian organisms of Britain 32 genera and 51 species pass up into the Carboniferous system.

Central Europe.—A large tract of Devonian rocks extends across the heart of Europe from the north of France through the Ardennes, the south of Belgium, and Rhenish Prussia, Westphalia and Nassau. But that the same rocks have a much wider spread under younger formations which cover them is shown by their reappearance far to the west in Brittany,[1] and to the east in the Harz and the Thuringer Wald. In the Belgian and Eifelian tracts they have been subdivided as under:

	Belgium and the North of France.[2]	Rhineland.[3]
UPPER.	Fammenien, consisting of two facies:	
	(*b*) Psammites du Condros (Condrusien), in which six zones are distinguished (*Cucullæa Hardingii, Spirifera Verneuili, Rhynchonella Dumonti, Orthis crenistria, Phacops latifrons, Palæopteris hibernica, Sphenopteris flaccida*, &c.).	(*c*) Sandstones and shales (*Spirifera Verneuili, Productus subaculeatus, Cucullæa Hardingii, Entomis* (*Cypridina*) *serrato-striata*).
	(*a*) Schistes de Famenne, divisible into four zones, (1) that of *Spirifera distans*, (2) of *Rhynchonella letiensis*, (3) of *Rhynchonella Dumonti*, (4) of *Rhynchonella Omaliusi*.	(*b*) Shales and marls (*Goniatites retrorsus, G. primordialis, Orthoceras subflexuosum, Bactrites gracilis, Pleurotomaria turbinea, Cardiola retrostriata, Entomis serrato-striata*, &c.).
	Frasnien, varying in composition and organic contents in different parts of the Devonian basins. In the Dinant basin it consists of	
	(*b*) Schistes de Matagne (*Goniatites retrorsus, Cardium palmatum, Camarophoria tumida, Bactrites subconicus, Entomis* (*Cypridina*) *serrato-striata*).	
	(*a*) Calcaires et schistes de Frasne, with abundant fossils (*Bronteus flabellifer, Goniatites intumescens, Spirifera Verneuili, Sp. pachyrhyncha, Sp. orbeliana, Spirigera concentrica, Atrypa reticularis, Rhynchonella cuboides, Camarophoria formosa, Receptaculites Neptuni*).	(*a*) Cuboides beds,—Nodular crumbling limestone (Kramenzelkalk), dolomitic marl, and shaly limestone (*Spirifera Verneuili, Sp. Urii, Atrypa reticularis, Rhynchonella cuboides, Productus subaculeatus, Camarophoria formosa, Receptaculites Neptuni*).

[1] A ridge of Devonian rocks stretches eastward under the south of England (where its existence has been proved by well-borings at London), and no doubt joins the Devonian area of the Boulonnais.

[2] See Dewalque's "Prodrome," Mourlon's "Géologie de la Belgique," and especially Gosselet's "Esquisse Géologique."

[3] See the elaborate series of papers by E. Kayser in the *Zeitschrift Deutsch. Geol. Gesell.* vols. xxii. (1870) to xxvi. F. Maurer, *N. Jahrb.* 1880, 1882.

	Belgium and the North of France.	Rhineland.
Middle.	Givetien. The great limestone of the middle Devonian series, well seen at Givet. Among the abundant characteristic fossils are *Spirifera mediotexta, Sp. undifera, Stringocephalus Burtini, Uncites gryphus, Megalodon cucullatus, Murchisonia coronata, M. bilineata, Cyathophyllum quadrigeminum, Heliolites porosa.* In the basin of Namur the conglomerate of Pairy-Bony lies below the limestone, and contains a band of sandstone with plants (*Lepidodendron Gaspianum*).	(*b*) Stringocephalus group, consisting of the great Eifel limestone with underlying crinoidal beds (*Stringocephalus Burtini, Spirifera undata, Productus subaculeatus, Pentamerus galeatus, Atrypa reticularis, Calceola sandalina,* and many corals and crinoids).
Lower.	Eifélien, Shales (Schistes de Couvin), with *Calceola sandalina, Phacops latifrons, Spirifera curvata, Sp. subcuspidata, Sp. elegans, Spirigera concentrica, Pentamerus galeatus, Strophalosia productoides,* &c.	(*a*) Calceola group,—marly limestones full of *Calceola sandalina, Spirifera concentrica, Camarophoria microrhyncha,* &c., resting upon impure shaly ferruginous limestone and greywacke, marked by an abundance of *Spirifera cultrijugata, Rhynchonella Orbignyana, Atrypa reticularis, Phacops latifrons,* &c.
	Coblenzien or Grauwacke, composed of four zones of greywacke, sandstones, shales, and conglomerate (Poudingue de Burnot, Ahrien, Hundsrückien), with *Pleurodictyum problematicum, Chonetes plebeia, Strophomena depressa, Strophomena daleidensis, Leptæna Murchisonii, Rhynchonella orbignyana, Spirifera subcuspidata, Sp. cultrijugata, Sp. paradoxa, Calceola sandalina,* numerous *Pterineæ.*	(*c*) Upper Greywacke (Vichterschichten), with *Chonetes sarcinulata, Ch. dilatata, Rhynchonella orbignyana,* numerous *Pterineæ.*
	Taunusien, consisting of the Grès d'Anor (*Spirifera paradoxa, Sp. Bischoffi, Spirigera undata,* &c.).	(*b*) Ahr group,—greywacke shales with *Chonetes sarcinulata, C. dilatata, Rhynchonella Livonica, Spirifera paradoxa, Sp. speciosa,* many species of *Pterinea, Pleurotomaria,* and *Murchisonia.*
	Gedinnien, comprising an upper group of shales and sandstones and a lower group of fossiliferous shales, quartzo-phyllades, quartzites, and conglomerates. The fossils in the lower group comprise *Dalmanites, Homalonotus Rœmeri, Primitia Jonesii, Tentaculites grandis, T. irregularis, Spirifera Mercuri, Orthis Verneuili, Pterinea ovalis,* &c.	(*a*) Coblentz group, greywacke and clay-slate (*Leptæna laticosta, Chonetes sarcinulata, Rhynchonella Livonica, Pleurodictyum problematicum,* &c.).

In the Harz, according to the researches of F. Roemer and K. A. Lossen, the Devonian system, which is there largely developed, consists of a lower group of quartzites, greywackes, flinty slates, clay slates, and associated bands of diabase, a middle group composed of the characteristic Stringocephalus-limestone with diabase tuffs, and an upper group consisting of limestones, shales, and schalsteins, with the usual *Spirifera Verneuili* and *Entomis serrato-striata.* Representatives of the same system reappear with local petrographical modifications, but with a remarkable

persistence of general palæontological characters, in Eastern Thuringia, Franconia, Saxony, Silesia, the north of Moravia, and East Galicia. Devonian rocks have been detected among the crumpled formations of the Styrian Alps by means of the evidence of abundant corals, clymenias, gasteropods, lamellibranchs, and other organic remains. Perhaps in other tracts of the Alps, as well as in the Carpathian range, similar shales, limestones, and dolomites, though as yet unfossiliferous, but containing ores of silver, lead, mercury, zinc, cobalt, and other metals, may be referable to the Devonian system. To the west of the central area the system has been recognized by its fossils in the Boulonnais, where it is well exposed. In the Palæozoic ridge of Brittany, also, as was many years ago shown by De Verneuil and De Gerville, the system is represented by a series of fossiliferous strata which in the lower part consist of sandstones, chiefly of greenish colours, alternating with shales and followed by courses of grey or black limestone and shale, above which lies an upper group of shales, crumbling micaceous sandstones, and some limestone. Again the central Silurian zone of the Pyrenees is flanked on the north and south by bands of Devonian rocks (with broad-winged spirifers and other characteristic fossils), which have been greatly disturbed and altered.

Throughout Central Europe there occurs, in many parts of the Devonian areas, evidence of contemporaneous volcanic action in the form of intercalated beds of diabase, diabase-tuff, schalstein, and porphyroid. These rocks are conspicuous in the "greenstone" tract of the Harz, in Nassau, Saxony, Westphalia, and the Fichtelgebirge. Here and there the tuff-bands are crowded with organic remains. It is also deserving of remark that over considerable areas (Ardennes, Harz, Sudeten-Gebirge, &c.) the Devonian sedimentary formations have assumed a more or less schistose character, and appear as quartzo-phyllades, quartzites, and other more or less crystalline rocks which were at one time supposed to belong to the Archæan series, but in which recognizable Devonian fossils have been found. At numerous places also they have been invaded by masses of granite, quartz-porphyry, or other eruptive rocks, round which they present the characteristic phenomena of contact metamorphism (p. 578). With these changes may have been connected the abundant mineral veins (Devon, Cornwall, Westphalia, &c.), whence large quantities of iron, tin, copper, and other metals have been obtained.

Russia.—In the north-east of Europe the Devonian and Old Red Sandstone types appear to be united, the limestones and marine organisms of the one being interstratified with the fish-bearing sandstones and shales of the other. In Russia, as was shown in the great work "Russia and the Ural Mountains" by Murchison, De Verneuil, and Keyserling, rocks intermediate between the Upper Silurian and Carboniferous Limestone formations cover an extent of surface larger than the British Islands. This wide development arises, not from the thickness, but from the undisturbed horizontal character of the strata. Like the Russian Silurian deposits, they remain to this day nearly as flat and unaltered as they were originally laid down. Judged by mere vertical depth, they present but a meagre representative of the massive Devonian greywacke and limestone of Germany, or of the Old Red Sandstone of Britain. Yet vast as is the area over which they constitute the surface rock, it probably forms only a small portion of their total

extent; for they are found turned up from under the newer formations along the flank of the Ural chain. It would thus seem that they spread continuously across the whole breadth of Russia in Europe. Though almost everywhere undisturbed, they afford evidence of some terrestrial oscillation between the time of their formation and that of the Silurian rocks on which they rest, for they are found gradually to overlap Upper and Lower Silurian beds.

The chief interest of the Russian rocks of this age, as was first signalized by Murchison and his associates, lies in the union of the elsewhere distinct Devonian and Old Red Sandstone types. In some districts these rocks consist largely of limestones, in others of red sandstones and marls. In the former they present molluscs and other marine organisms of known Devonian species; in the latter they afford remains of fishes, some of which are specifically identical with those of the Old Red Sandstone of Scotland. The distribution of these two palæontological facies in Russia is traced by Murchison to the lithological characters of the rocks, and consequent original diversities of physical conditions, rather than to differences of age. Indeed, cases occur where in the same band of rock Devonian shells and Old Red Sandstone fishes lie commingled. In the belt of the formation which extends southwards from Archangel and the White Sea, the strata consist of sands and marls, and contain only fish remains. Traced through the Baltic provinces, they are found to pass into red and green marls, clays, thin limestones, and sandstones, with beds of gypsum. In some of the calcareous bands such fossils occur as *Orthis striatula*, *Spiriferina prisca*, *Leptæna productoides*, *Spirifera calcarata*, *Spirorbis omphaloides*, and *Orthoceras subfusiforme*. In the higher beds *Holoptychius* and other well-known fishes of the Upper Old Red Sandstone occur. Followed still further to the south, as far as the watershed between Orel and Woronesch, the Devonian rocks lose their red colour and sandy character, and become thin-bedded yellow limestones, and dolomites with soft green and blue marls. Traces of salt deposits are indicated by occasional saline springs. It is evident that the geographical conditions of the Russian area during the Devonian period must have closely resembled those of the Rhine basin and central England during the Triassic period.

The Russian Devonian rocks have been classified as follows:

Upper	Red and white sandstone and green marls,—numerous fish remains, particularly *Holoptychius nobilissimus*, *Glyptosteus favosus*, *Diplopterus macrocephalus*.
Middle	Limestones, clays, marls, dolomite, and gypsum,—numerous characteristic Devonian shells and crinoids, also *Holoptychius nobilissimus*.
Lower	In some districts red and green limestones with red marls and Middle Devonian fossils; in others (North Livonia) sandstones and clays, with numerous fish remains of the genera *Osteolepis*, *Dipterus*, *Diplopterus*, *Asterolepis*, and others found also in the Caithness flags of Scotland.

There is an unquestionable passage of the uppermost Devonian rocks of Russia into the base of the Carboniferous system.

North America.—The Devonian system, as developed in the northern States, and eastern Canada and Nova Scotia, presents much

geological interest in the union which it contains of the same two distinct petrographical and biological types found in Europe. Traced along the Alleghany chain through Pennsylvania into New York, the Devonian rocks are found to contain a characteristic suite of marine organisms comparable with those of the Devonian system of Europe. But on the eastern side of the great range of Silurian hills in the north-eastern States, we encounter in New Brunswick and Nova Scotia a succession of red and yellow sandstones, limestones, and shales nearly devoid of marine organisms, yet full of land-plants, and with occasional traces of fish remains.

The marine or Devonian type has been grouped in the following subdivisions by the geologists of New York:

UPPER DEVONIAN	Catskill Red Sandstone. Chemung group. Portage group. Genesee group. Hamilton group. Marcellus group.
LOWER DEVONIAN	Corniferous or Upper Helderberg group. Schoharie Grit. Cauda-galli Grit.

In the Lower Devonian series traces of terrestrial plants (*Psilophyton*, *Caulopteris*, &c.) have been detected, even as far west as Ohio. Corals (cyathophylloid forms, with *Favosites*, *Syringopora*, &c.) abound, especially in the Corniferous Limestone, perhaps the most remarkable mass of coral-rock in the American Palæozoic series, and from which Hall has made a magnificent collection of specimens. Among the brachiopods are species of *Pentamerus*, *Stricklandinia*, *Rhynchonella*, and others, with the characteristic European form *Spirifera cultrijugata*, and the world-wide *Atrypa reticularis*. The trilobites include the genera *Dalmanites*, *Proëtus*, and *Phacops*. The earliest known traces of American fishes occur in the Corniferous group. They consist of ichthyodorulites, and teeth of cestraciont and hybodont placoids, and plates, bones, and teeth of some peculiar ganoids (*Macropetalichthys*, *Onychodus*).

In the Hamilton formation (embracing the Marcellus shale, the Hamilton beds, and the Genesee shale) remains of land-plants occur, but much less abundantly than among the rocks of New Brunswick. Brachiopods are especially abundant among the sandy beds in the centre of the formation. They comprise, as in Europe, many broad-winged spirifers (*S. mucronatus*, &c.), with species of *Productus*, *Chonetes*, *Athyris*, &c. The earliest American goniatites have been noticed in these beds. Newberry has described a gigantic fish (*Dinichthys*) from the Black Shale of Ohio.

The Portage and Chemung groups have yielded land-plants and fucoids, also some crinoids, numerous broad-winged spirifers, with *Aviculæ*, and a few other lamellibranchs. These strata in the New York region consist of shales and laminated sandstones, which attain a maximum thickness there of upwards of 2000 feet, but die out entirely towards the interior. They are covered by a mass of red sandstones and conglomerates—the Catskill group, which is 2000 or 3000 feet deep in the Catskill Mountains, and thickens along the Appalachian region to 5000 or 6000 feet. These red arenaceous rocks bear a striking similarity in their lithological and biological characters to the Old Red Sandstone of Europe.

As a whole they are unfossiliferous, but they have yielded some ferns like those of the Upper Old Red Sandstone of Ireland and Scotland (*Palæopteris*), some characteristic genera of fish, as *Holoptychius* and *Bothriolepis*, and a large lamellibranch closely resembling the Irish *Anodonta*. The Old Red Sandstone development, found on the eastern side of the crystalline ridge which runs southward from Canada far into the States, is described at p. 718.

II. OLD RED SANDSTONE TYPE.

§ 1. General Characters.

Under the name of Old Red Sandstone is comprised a vast and still imperfectly described series of red sandstones, shales, and conglomerates, intermediate in age between the Ludlow rocks of the Upper Silurian and the base of the Carboniferous system in Britain. These rocks were termed "Old" to distinguish them from a somewhat similar series overlying the Coal-measures, to which the name "New" Red Sandstone was applied. When the term Devonian was adopted, it speedily supplanted that of Old Red Sandstone, inasmuch as it was founded on a type of marine strata of wide geographical extent, whereas the latter term described what appeared to be merely a British and local development. For the reasons already given, however, it is desirable to retain the title Old Red Sandstone as descriptive of a remarkable suite of deposits to which there is little or nothing analogous in typical Devonian rocks. The Old Red Sandstone of Europe is almost entirely confined to the British Isles. It was deposited in separate areas or basins, the sites of some of which can still be traced. Their diversities of sediment and discrepance of organic contents point to the absence, or at least rare existence, of any direct communication between them. It was maintained many years ago by Mr. Godwin Austen, and has been more recently enforced by Sir A. C. Ramsay, that these basins were lakes or inland seas. The character of the strata, the absence of unequivocally marine fossils, the presence of land plants and of numerous ganoid fishes which have their modern representatives in rivers and lakes, suggest and support this opinion, which has been generally adopted by geologists. The red arenaceous and marly beds which, with their fish remains and land plants, occupy a depth of many thousand feet between the top of the Upper Silurian and the base of the Lower Carboniferous systems, are regarded as the deposits of a series of lakes or inland seas formed by the uprise of portions of the Silurian sea-floor. The length of time during which these lacustrine basins must have existed is shown, not only by the thickness of the deposits formed in them, but by the complete change which took place in the marine fauna between the close of the Silurian and the commencement of the Carboniferous period. The

prolific fauna of the Wenlock and Ludlow rocks was driven away from Western Europe by the geographical revolutions which, among other changes, produced the lake-basins of the Old Red Sandstone. When a marine population—crinoids, corals, and shells—once more overspread that area, it was a completely different one. So thorough a change must have demanded a long interval of time.

Rocks.—As shown by the name of the type, red sandstone is the predominant rock. The colour varies from a light brick-red to a deep chocolate-brown, and occasionally passes into green, yellow, or mottled tints. The sandstones are for the most part granular siliceous rocks, where the component grains of clear quartz are coated and held together by a crust of earthy ferric oxide. Scattered pebbles of quartz or of various crystalline rocks are frequently noticeable among the sandstones, and this character affords a passage into conglomerate. The latter rock forms a conspicuous feature in many Old Red Sandstone districts. It varies in thickness from a mere thin bed up to successive massive beds, having a united thickness of several thousand feet. The pebbles vary much in composition. In some beds they are chiefly of quartz, in others of granite, syenite, quartz-porphyry, gneiss, greywacke, or other crystalline or compact rocks. They are sometimes tolerably angular, particularly where the conglomerate rests upon schists or other rocks which weather into angular blocks. In the upper Old Red Sandstone, thick accumulations of subangular conglomerate or breccia recall some glacial deposits of modern times. For the most part the stones in the conglomerates are well rounded, sometimes indeed remarkably so, even when they are a foot or more in diameter. Their size ranges up to blocks five feet or more in length; but these larger masses are usually angular fragments that have been derived from rocks in the immediate neighbourhood. The smaller rounded blocks must often have come from some distance; at least it is impossible to discover any near source for them. Bands of red and green clay or marlite occur, in which seams and nodules of cornstone may not infrequently be observed. Here and there, too, the sandstones assume a flaggy character, and sometimes pass into fine grey or olive-coloured shales and flagstones. Organic remains occur in some of these grey beds, but are usually absent from the red strata, though in some of the conglomerates teeth, scales, and broken bones of fishes are not uncommon. In the north of Scotland peculiar very hard calcareous and bituminous flagstones are largely developed, and have yielded the chief part of the remarkable ichthyic fauna of the system. In Scotland, also, contemporaneously erupted porphyrites, felsites, and tuffs play an important part in the petrography of the Old Red Sandstone, seeing that they attain a thickness in some places of more than 6000 feet, and form important ranges of hills.

Life.—No greater contrast is to be found between the organic contents of any two successive groups of rock than that which is presented by a comparison of the Upper Silurian and Old Red Sand-

stone systems of Western Europe. The abundant marine fauna of the Ludlow period entirely disappeared from the region. As soon as the red rocks begin, the fossils rapidly die out. Yet that the Upper Silurian fauna continued to live on outside of the Old Red Sandstone areas is proved by the occurrence of Silurian species of *Orthoceras*, *Graptolite*, &c., in a zone of the Scottish Old Red Sandstone 5000 feet above the bottom of the system. On the land that surrounded the lakes or inland seas of the period, there grew the oldest terrestrial vegetation of which more than mere fragments are known. It has been scantily preserved in the ancient lake-bottoms in Europe; more abundantly in Gaspé and New Brunswick. The American localities have yielded to the researches of Principal Dawson of

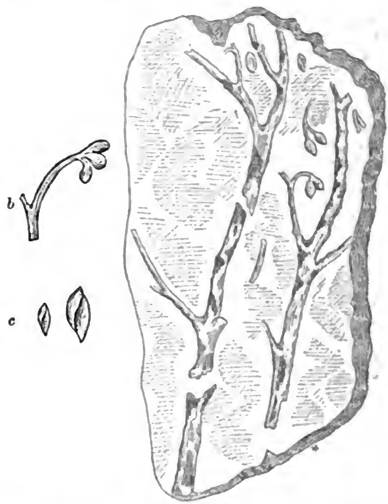


Fig. 331.—Psilophyton robustum (Dawson). Lower Old Red Sandstone, Perthshire. Drawn by Mr. R. Kidston.

a, specimen of the plant ½ nat. size; *b*, fructification; *c*, empty spore-cases.

Montreal no fewer than 118 species of land-plants. They are almost all acrogens, lycopods and ferns being largely predominant. Among the distinctive forms the following may be mentioned:—*Psilophyton* (Fig. 331), *Arthrostigma*, *Leptophleum*, and *Prototaxites*. Forty-nine ferns include the genera *Palæopteris* (*Cyclopteris*), *Neuropteris*, *Sphenopteris*, and some tree-ferns (*Psaronius*, *Caulopteris*). Lepidodendroid and sigillaroid plants abound, as well as calamites. Higher forms of vegetation are represented by a few

conifers (*Dadoxylon, Ormoxylon*,[1] &c.). From a locality on Lake Erie, Dr. Dawson describes a fragment of dicotyledonous wood, not unlike that of some modern trees—the most ancient fragment of

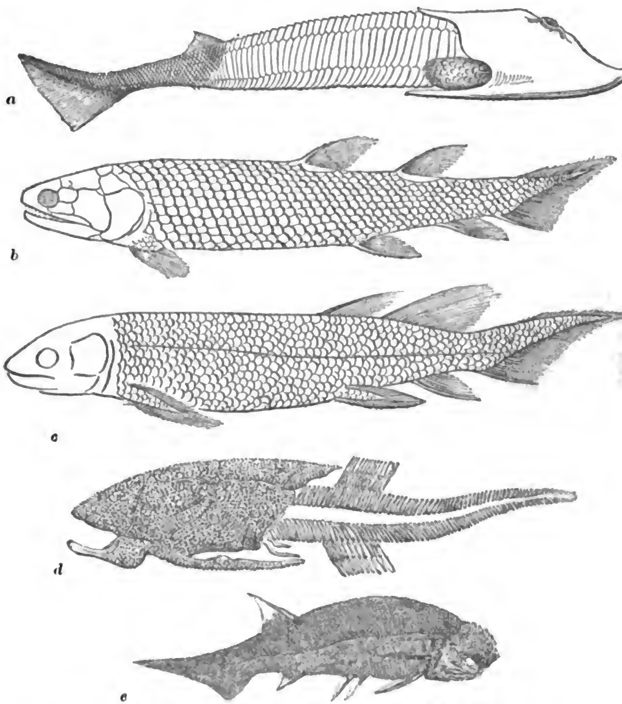


FIG. 332.—LOWER OLD RED SANDSTONE FISHES.

a, Cephalaspis Lyelli (Ag.) (side view), restored by Prof. E. Ray Lankester, F.R.S.; *b*, Osteolepis microlepidotus (Sedgw. and Murch.), restored by Dr. R. H. Traquair, F.R.S.; *c*, Dipterus Valenciennesii (Sedgw. and Murch.), from a sketch by Dr. Traquair; *d*, Coccosteus decipiens (Ag.); *e*, Acanthodes Mitchelli (Eg.), Forfarshire, from a sketch by Mr. B. N. Peach.

an angiospermous exogen yet discovered. So abundant are these vegetable remains that in some layers they actually form thin seams of coal.

[1] *Prototaxites*, included by Dr. Dawson among the Coniferæ, is relegated by Mr. Carruthers to the Algæ under the name of *Nematophycus*—a genus also found in the Upper Silurian rocks of N. Wales.—*Month. Microscopical Journ.* 1872.

The interest of this flora is heightened by the discovery of the fact that the primeval forests were not without the hum of insect life. The most ancient known relics of insect forms have been recovered from the Devonian strata of New Brunswick. They are all neuropterous wings, and have been referred by Mr. Scudder of Boston to four species combining a remarkable union of characters now found in distinct orders of insects. In one fragment he observed a structure which he could only compare to the stridulating organ of some male *Orthoptera*. Another wing indicates the existence of a gigantic *Ephemera*, with a spread of wing extending to five inches.

The existence of myriapods in the forests of this ancient period has recently been shown by Mr. B. N. Peach, who finds that the so-called *Kampecaris*, hitherto regarded as a larval form of isopod crustacean, really contains two genera of chilognathous myriapods, differing from other known forms, fossil and recent, in their less differentiated structure, each body segment being separate, and supplied with only one pair of walking legs.

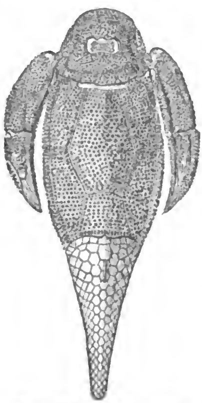


Fig. 333.—Pterichthys cornutus (Ag.).

The water-basins of the Old Red Sandstone were, on the whole, singularly devoid of life; at least, remains of it have been but meagrely preserved. The fauna consists almost wholly of fishes. Among these the *Pteraspis* survived for a while from Upper Silurian times. With it there lived other members of the same sub-order of placodermatous ganoids, notably the curious saddler's knife-like *Cephalaspis*, the allied *Auchenaspis*, the *Coccosteus*, and *Pterichthys* (Fig. 332). The sub-order of Acanthodians attained its chief development in these lakes, the genera *Acanthodes*, *Diplacanthus*, and *Cheiracanthus* being characteristic and abundant. The *Crossopterygidæ*, so remarkable for the central scaly lobe of their fins and represented at the present time by *Polypterus*, swarmed in the waters, some of the most characteristic genera being *Osteolepis*, *Diplopterus*, *Holoptychius*, *Glyptolepis*, *Phaneropleuron*, *Glyptolæmus*, *Glyptopomus*. The modern *Ceratodus* of the Queensland rivers had a closely allied representative in the abundant *Dipterus* of the Old Red Sandstone lakes. The largest fish of the European basin was the *Asterolepis*, the cuirass-like cephalic shield of which sometimes reaches a length of twenty, with a breadth of sixteen inches. Probably more gigantic was the *Dinichthys*, already referred to as occurring in the Devonian rocks of North America, of which the head, encased in strong plates, attained a length of three feet, and was armed with a formidable apparatus of teeth.

A few eurypterid crustacea occur, especially of the genera

Eurypterus and *Pterygotus*. The species of the former are small, but one of the latter, *P. anglicus* (Fig. 329), is found in Scotland, which must have had a length of five or six feet.

§ 2.—Local Development.

Murchison, who strongly advocated the opinion that the Old Red Sandstone and Devonian rocks represent different geographical conditions of the same period, and who had with satisfaction seen the adoption of the Devonian classification by Continental geologists, endeavoured to trace in the Old Red Sandstone of Britain a threefold division, like that which had been accepted for the Devonian system. He accordingly arranged the formations as in the subjoined table:

Old Red Sandstone as classified by Murchison.	Upper.	Yellow and red sandstones and conglomerates (*Pterichthys major*, *Holoptychius nobilissimus*, &c.) = Dura Den beds.
	Middle.	Grey and blue calcareous and bituminous flagstones, limestones, and red sandstones, and conglomerates (*Dipterus*, *Osteolepis*, *Asterolepis*, *Acanthodes*, *Pterichthys*, &c.) = Caithness flags.
	Lower.	Red and purple sandstones, grey sandy flagstones, and coarse conglomerates (*Cephalaspis*, *Pteraspis*, *Pterygotus*) = Arbroath flags.

It is important to observe that in no district can these three subdivisions be found together, and that the so-called "middle" formation occurs only in one region—the north of Scotland. The classification, therefore, does not rest upon any actually ascertained stratigraphical sequence, but on an inference from the organic remains. The value of this inference will be estimated a little further on. All that can be affirmed from stratigraphical evidence in any Old Red Sandstone district in Britain is that a great physical and palæontological break can generally be traced in the Old Red Sandstone, dividing it into two completely distinct series.

As a whole, the Old Red Sandstone, where its strata are really red, is, like other masses of red deposits, singularly barren of organic remains. The physical conditions under which the precipitation of iron oxide took place were evidently unfavourable for the development of animal life in the same waters. Sir A. C. Ramsay has connected the occurrence of such red formations with the existence of salt lakes, from the bitter waters of which not only iron oxide but often rock-salt, magnesian limestone, and gypsum were thrown down.[1] He points also to the presence of land plants, footprints of amphibia, and other indications of terrestrial surfaces, while truly marine organisms are either found in a stunted condition or are absent altogether. Where the strata of the Old Red Sandstone, losing their red colour and ferruginous character, assume grey or yellow tints and pass into a calcareous or argillaceous condition, they

[1] Professor Gosselet contends that the precipitation of iron might quite well have taken place in the sea, and he cites the case of the Devonian basin of Dinant, where the same beds are in one part red and barren of organic remains, and in another part of the same area are of the usual colours, and are full of marine fossils. But the red colour of the Old Red Sandstone is general, and is accompanied with other proofs of isolation in the basins of deposit.

not infrequently become fossiliferous. At the same time it is not unworthy of remark that some of the red conglomerates, which might be supposed little likely to contain organic remains, are occasionally found to be full of detached scales, plates, and bones of fishes.

The Old Red Sandstone of Britain, according to the author's researches, consists of the following subdivisions:

2. Upper.—Yellow and red sandstones, conglomerates, marls, &c., passing up conformably into the base of the Carboniferous system, and resting unconformably on the Lower Old Red Sandstone and every older formation—*Holoptychius*, *Pterichthys major*, &c.

1. Lower.—Red sandstones, conglomerates, flagstones, and associated igneous rocks, passing in some places conformably down into Upper Silurian formations—*Dipterus*, *Coccosteus*, *Cephalaspis*, *Pterygotus*, &c.

Lower.—In a memoir on the Old Red Sandstone of Western Europe, the author has proposed short names for the different detached basins in which the Lower Old Red Sandstone was accumulated.[1] The most southerly of these (the Welsh Lake) lies in the Silurian region extending from Shropshire into South Wales. Here the uppermost parts of the Silurian system graduate into red strata, not less than 10,000 feet thick, which in turn pass up conformably into the base of the Carboniferous system. This vast accumulation of red rocks consists in its lower portions of red and green shales and flagstones, with some white sandstones and thin cornstones; in the central and chief division, of red and green spotted sandy marls and clays, with red sandstones and cornstones; in the higher parts, of grey, red, chocolate-coloured, and yellow sandstones, with bands of conglomerate. No unconformability has yet been detected in any part of this series of rocks, though, from the observations of De la Beche, it may be suspected that the higher strata, which graduate upward into the Carboniferous formations, are separated from the underlying portions of the Old Red Sandstone by a distinct discordance.

Although, as a whole, barren of organic remains, these red rocks have here and there, more particularly in the calcareous zones, yielded fragments of fishes and crustaceans. In their lower and central portions remains of the ganoids *Cephalaspis*, *Didymaspis*, *Scaphaspis*, *Pteraspis*, and *Cyathaspis* have been found, together with crustaceans of the genera *Stylonurus*, *Pterygotus*, and *Prearcturus*, and obscure traces of plants. The upper yellow and red sandstones contain none of the cephalaspid fishes, which are there replaced by *Pterichthys* and *Holoptychius*, associated with distinct impressions of land-plants. In some of the higher parts of the Old Red Sandstone of South Wales and Shropshire, *Serpula* and *Conularia* occur; but these are exceptional cases, and point to the advent of the Carboniferous marine fauna, which doubtless existed outside the British area before it spread over the site of the Old Red Sandstone basins.

It is in Scotland that the Old Red Sandstone shows the most complete and varied development, alike in physical structure and in organic contents. Throughout that country the system is found everywhere to present a division into two well-marked groups of strata, separated from each other by a strong unconformability and a complete break in the succession of organic remains. It occurs in distinct basins of deposit. One of these occupies the central valley between the base of the Highland

[1] *Trans. Roy. Soc. Edin.* vol. xxviii. 1879.

mountains and the uplands of the southern counties (Lake Caledonia). On the north-east it is cut off by the present coast-line from Stonehaven to the mouth of the Tay. On the south-west it ranges by the island of Arran across St. George's Channel into Ireland, where it runs almost to the western sea-board, flanked on the north, as in Scotland, by hills of crystalline rocks, and on the south chiefly by a Lower Silurian belt. Another distinct and still larger basin (Lake Orcadie) lies on the north side of the Highlands, but only a portion of it comes within the present area of Scotland. It skirts the slopes of the mountains along the Moray Firth and the east of Ross and Sutherland, and stretches through Caithness and the Orkney Islands as far as the south of the Shetland group. It may possibly have been at one time continued as far as the Sognefjord and Dalsfjord in Norway, where red conglomerates, like those of the north of Scotland, occur. There is even reason to infer that it may have ranged eastwards into Russia, for, as already stated, some of its most characteristic organisms are found also among the Devonian strata of that country. A third minor area of deposit (Lake Cheviot) lay on the south side of the southern uplands over the east of Berwickshire and the north of Northumberland, including the area of the Cheviot Hills. A fourth (Lake of Lorne) occupied a basin on the flanks of the south-west Highlands, which is now partly marked by the terraced volcanic hills of Lorne. There is sufficient diversity of lithological and palæontological characters to show that these several areas were on the whole distinct basins, separated both from each other and from the sea.

In the central basin or Lake Caledonia, the twofold division of the Old Red Sandstone is typically seen. The lower series of deposits attains a maximum depth of upwards of 20,000 feet. These strata everywhere present traces of shallow-water conditions. The accumulation of so great a thickness can only be explained on the supposition that the subterranean movements which at first ridged up the Silurian sea-floor into land, enclosing separate basins, continued to deepen these basins until eventually enormous masses of sediment had slowly gathered in them. There are proofs that the subsidence was interrupted by occasional local elevations. In Lanarkshire this massive series of deposits passes down conformably into Upper Silurian rocks; elsewhere its base is concealed by later formations, or by the unconformability with which different horizons rest upon the older rocks. It is covered unconformably by every formation younger than itself. It consists of reddish-brown or chocolate-coloured, grey, and yellow sandstones, red shales, grey flagstones, coarse conglomerates, and occasional bands of limestone and cornstone. The grey flagstones and thin grey and olive shales and "calmstones" are almost confined to Forfarshire, in the north-east part of the basin, and are known as the Arbroath flags. One of the most marked lithological features in this central Scottish basin is the occurrence in it of prodigious masses of interbedded volcanic rocks. These, consisting of porphyrite-lavas, felsites, and tuffs, attain a thickness of more than 6000 feet, and form important chains of hills, as in the Pentland, Ochil, and Sidlaw ranges. They lie several thousand feet above the base of the system, and are regularly interstratified here and there with bands of the ordinary sedimentary strata. They point to the outburst of numerous volcanic vents along the lake or inland sea in which the Lower Old Red Sandstone of central Scotland was laid down; and their disposi-

tion shows that the vents ranged themselves in lines or linear groups parallel with the general trend of the great central valley. The fact that the igneous rocks are succeeded by thousands of feet of sandstones, shales, and conglomerates, without any intercalation of lava or tuff, proves that the volcanic episode in the history of the lake came to a close long before the lake itself disappeared. As a rule the deposits of this basin are singularly unfossiliferous, though some portions of them, particularly in the Forfarshire (Arbroath) flagstone group, have proved rich in fish remains. In Lanarkshire about 5000 feet above the base of the system a thin band of shale occurs, containing a graptolite, with *Spirorbis Lewisii* and *Orthoceras dimidiatum*,—undoubtedly Upper Silurian forms. This interesting fact serves to indicate that, though geographical changes had elevated the Upper Silurian sea-floor partly into land and partly into isolated inland water-basins, the sea outside still contained an Upper Silurian fauna, which was ready on any favourable opportunity to re-enter the tracts from which it had been excluded (see p. 628). The interval of its reappearance seems to have been very brief, however, for the band of shale containing these Upper Silurian marine organisms is only a few inches thick, and the fossils have not been detected on any other horizon. With these exceptions, the fauna of the formation consists entirely of fishes and crustaceans. Nine or more species of crustaceans have been obtained, chiefly eurypterids, but including one or two phyllopods. The large pterygotus (*P. Anglicus*) is especially characteristic, and must have attained a great size, for some of the individuals indicate a length of 6 feet with a breadth of 1½ feet. There occur also a smaller species (*P. minor*), two *Eurypteri*, three species of *Stylonurus*, and abundant clusters of crustacean egg-packets (*Parka decipiens*). Seventeen species of fishes have been obtained, chiefly from the Arbroath flags. They belong to the sub-orders *Acanthodidæ* and *Ostracostei* (Fig. 332). One of the most abundant forms is the little *Acanthodes Mitchelli*. Another common fish is *Diplacanthus gracilis*. There occur also *Climatius scutiger*, *C. reticulatus*, and *C. uncinatus*, *Parexus incurvus*, *Euthacanthus* (four species), *Cephalaspis Lyellii*, and *Pteraspis Mitchelli*. Some of the sandstones and shales are crowded with indistinctly preserved vegetation, occasionally in sufficient quantity to form thin laminæ of coal. In Forfarshire the surfaces of the shaly flagstones are now and then covered with linear grass-like plants like the sedgy vegetation of a lake or marsh. In Perthshire certain layers occur chiefly made up of compressed stems of *Psilophyton* (Fig. 331). The adjoining land was doubtless clothed with a flora in large measure lycopodiaceous.

The Old Red Sandstone of the northern basin (Lake Orcadie) is typically developed in Caithness, where it consists chiefly of the well-known dark-grey bituminous and calcareous flagstones of commerce. It rests unconformably upon metamorphosed Lower Silurian schists, and must have been deposited on the very uneven bottom of a sinking basin, seeing that occasionally even some of the higher platforms are found resting against the schists and granites. The lower zones consist of red sandstones and conglomerates, which graduate upward into the flagstones. Other red sandstones, however, supervene in the higher parts of the system. The total depth of the series in Caithness has been estimated at upwards of 16,000 feet. Murchison was the first to attempt the correlation of the Caithness flagstones with the Old Red Sandstone of the rest of Britain.

Founding upon the absence from these northern rocks of the characteristic cephalaspidean fishes of the admitted Lower Old Red Sandstone of the south of Scotland and of Wales and Shropshire, upon the presence of numerous genera of fishes not known to occur in the true Lower Old Red Sandstone, and upon the discovery of a *Pterygotus* in the basement red sandy group of strata, he concluded that the massive flagstone series of Caithness could not be classed with the Lower Old Red Sandstone, but must be of younger date. He supposed these red sandstones, conglomerates, and shales at the base, with their *Pterygotus*, to represent the true Lower Old Red Sandstone, while the great flagstone series with its distinctive fishes was made into a middle division answering in some of its ichthyolitic contents to the Middle Devonian rocks of the Continent. This view has been accepted by geologists. Recently, however, I have endeavoured to show that the Caithness flagstones belong to the Lower Old Red Sandstone, and that there is no evidence of the existence of any middle division. It appears to me that the discrepance in organic contents between the Caithness and the Arbroath flags is by no means so strong as Murchison supposed, but that several species are common to both. In particular, I find that the characteristically Lower Old Red Sandstone and Upper Silurian crustacean genus *Pterygotus* occurs, not merely in the basement zone of the Caithness flags, but also high up in the series. The genera *Acanthodes* and *Diplacanthus* are abundant both in Caithness and in Forfarshire. *Parexus incurvus* occurs in the northern as well as the southern basin. The admitted palæontological distinctions are probably not greater than the striking lithological differences between the strata of the two regions would account for, or than the contrast between the ichthyic faunas of contiguous water-basins at the present time.

Somewhere about sixty species of fishes have been obtained from the Old Red Sandstone of the north of Scotland. Among these the genera *Acanthodes*, *Asterolepis*, *Cheiracanthus*, *Cheirolepis*, *Coccosteus*, *Diplacanthus*, *Diplopterus*, *Dipterus*, *Glyptolepis*, *Osteolepis*, and *Pterichthys* are specially characteristic. Some of the shales are crowded with the little ostracod crustacean *Estheria membranacea*. Land plants abound, especially in the higher groups of the flagstones, where forms of *Psilophyton*, *Lepidodendron*, *Stigmaria*, *Sigillaria*, *Calamites*, and *Cyclopteris*, as well as other genera, occur. In the Shetland Islands traces of abundant contemporaneous volcanic rocks have been observed. These, with the exception of two trifling examples in the region of the Moray Firth, are the only known instances of volcanic action in the Lower Old Red Sandstone of Lake Orcadie. In the other two Scottish basins, those of the Cheviot Hills and of Lorne, volcanic action continued long vigorous, and produced thick piles of lava, like those of Lake Caledonia.

Upper.—Below the Carboniferous system there occur in Scotland certain red sandstones, deep red clays or marls, conglomerates, and breccias, the sandstones passing into yellow or even white. These strata, wherever their stratigraphical relations can be distinctly traced, lie unconformably upon every formation older than themselves, including the Lower Old Red Sandstone, while on the other hand they pass up conformably into the Carboniferous rocks above. Studied from the side of the underlying formations, they seem naturally to form part of the Old Red Sandstone, since they agree with it in general lithological

character, and also in containing some distinctively Old Red Sandstone genera of fishes, such as *Pterichthys* and *Holoptychius;* though, approached from the upper or Carboniferous direction, they might rather be assumed as the natural sandy base of that system into which they insensibly graduate. On the whole, they are remarkably barren of organic remains, though in one locality—Dura Den in Fife—they have yielded a number of genera and species of fishes, crowded profusely through the pale sandstone as if the individuals had been suddenly killed and rapidly covered over with sediment. Among the characteristic organisms of the Scottish Upper Old Red Sandstone are *Pterichthys major*, *Holoptychius nobilissimus*, *H. Andersoni*, *Glyptopomus*, *Glyptolæmus*, and *Phaneropleura*.

An interesting fact deserves mention here as a corollary to what has been stated above regarding the survival for some time of an Upper Silurian fauna outside the area of the British Old Red Sandstone lakes. In the Upper Old Red Sandstone of the basin of the Firth of Clyde, *Pterichthys major* and *Holoptychius* occur at the Heads of Ayr, while a band of marine limestone lying in the heart of the red sandstone series in Arran is crowded with ordinary Carboniferous Limestone shells, such as *Productus giganteus*, *P. semireticulatus*, *P. punctatus*, *Chonetes hardrensis*, *Spirifera lineata*, &c. None of these fossils has been detected in the great series of red sandstones overlying the limestone. They do not reappear till we reach the limestones in the Lower Carboniferous series; yet the organisms must have been living during all that long interval outside of the Upper Old Red Sandstone area (p. 739). Not only so, but they must have been in existence long before the formation of the thick Arran limestone, though it was only during the comparatively brief interval represented by that limestone that geographical changes permitted them to enter the Old Red Sandstone basin and settle for a while on its floor. Thus we see that while, on the one hand, the older parts of the Lower Old Red Sandstone were coeval with an Upper Silurian fauna which, having disappeared from the area of Britain, survived outside of that area, on the other hand, the higher parts of the Upper Old Red Sandstone were contemporaneous with a Carboniferous Limestone fauna which, having appeared beyond the British area, was ready to spread over it as soon as the conditions became favourable for the invasion. It is, of course, obvious that such an abundant and varied fauna as that of the Carboniferous Limestone cannot have come suddenly into existence at the period marked by the base of the limestone. It must have had a long previous existence outside the present area of the deposit. But it is seldom that we obtain such clear evidence of this palæontological relation as in these instances from the Scottish Old Red Sandstone.

In the north of Scotland, on the lowlands bordering the Moray Firth, and again in the island of Hoy, one of the Orkney group, yellow and red sandstones, sometimes containing characteristic Upper Old Red Sandstone fishes, are found lying unconformably upon the Caithness flags. In these northern tracts the same relation is thus traceable as in the central counties between the two divisions of the system.

Turning southward across the border districts, we trace the red sandstones and conglomerates of the Upper Old Red Sandstone lying unconformably on Silurian rocks and Lower Old Red Sandstone. Some of the brecciated conglomerates have much resemblance to glacial detritus, and it has been suggested that they have been connected with

contemporaneous ice-action. Such are the breccias of the Lammermuir Hills, and those which show themselves here and there from under the overlying mass of Carboniferous strata that flanks the Silurian hills of Cumberland and Westmoreland. Red conglomerates and sandstones appear interruptedly at the base of the Carboniferous rocks even as far as Flintshire and Anglesea. They are commonly classed as Old Red Sandstone, but merely from their position and lithological character. No organic remains have been found in them. They may therefore, in part at least, belong to the Carboniferous system, having been deposited on different successive horizons during the gradual depression of the land. In Devonshire, at Barnstaple, Pilton, Marwood, and Baggy Point, certain sandstones, shales, and limestones (already referred to in the account of the Devonian rocks) graduate upward into the base of the Carboniferous system, and appear to represent the Upper Old Red Sandstone of the rest of Britain. They contain land plants and also many marine fossils, some of which are common Carboniferous forms. They thus indicate a transition into the geographical conditions of the Carboniferous period, as is still more clearly illustrated by the corresponding strata in Scotland.

The Old Red Sandstone attains a great development in the south and south-west of Ireland. The "Glengariff grits," some 10,000 feet thick, pass down into Upper Silurian strata, and may, perhaps, represent the Lower Old Red Sandstone of Scotland. The rocks are covered unconformably by the "Old Red Sandstone" of Irish geologists, which may be the equivalent of the Scottish Upper Old Red Sandstone. This overlying mass of sedimentary material consists of two members, a lower very thick series of green, purple, and reddish grits or slates and an upper thin set of grey or yellowish flagstones. They have yielded a few fishes (*Bothriolepis*, *Coccosteus*, *Pterichthys*, *Glyptolepis*), some crustaceans (*Belinurus*, *Pterygotus*), a fresh-water lamellibranch (*Anodonta Jukesii*), and a number of ferns and other land plants (*Palæopteris*, *Sphenopteris*, *Sagenaria*, *Knorria*, *Cyclostigma*).[1]

Norway, &c.—On the continent of Europe the Old Red Sandstone type can hardly be said to occur. Some outliers of red sandstone and conglomerate (p. 713) in northern and western Norway reach a thickness of 1000 to 1200 feet. Near Christiania they follow the Silurian strata like the Old Red Sandstone, but as yet have yielded no fossils, so that, as they pass up into no younger formation, their geological horizon cannot be certainly fixed. The Devonian rocks of Russia have been above referred to as presenting a union of the two types of this part of the geological series. The extension of the land of the Old Red Sandstone period, with its characteristic flora, far north within the Arctic circle is indicated by the discoveries made a few years ago at Bear Island (lat. 70° 30′ N.) between the coast of Norway and Spitzbergen. Certain seams of coal and coaly shale occur at that locality underlying beds of Carboniferous limestone and overlying some yellow dolomite, calcareous shale, and red shales. They have been assigned by Heer to the Carboniferous series, but are regarded by Dawson as unquestionably Devonian. They may be correlated with the Upper Old Red Sandstone of Britain. Heer enumerates eighteen species; only three are peculiar to the locality, while among

[1] Prof. Hull has recently devoted much attention to the correlation of these Irish rocks. See in particular his papers in *Q. J. Geol. Soc.* xxxv., xxxvi., *Proc. Roy. Dublin Soc.* (new ser.), 1880.

the others are some widely-diffused forms,—*Calamites radiatus* (*transitionis*), *Palæopteris roemeriana*, *Sphenopteris Schimperi*, *Cardiopteris frondosa*, *Lepidodendron veltheimianum*, and three other species, *Knorria imbricata*, and *Cyclostigma kiltorkense*.[1]

North America.—It is interesting to observe that in North America representatives occur of the two divergent Devonian and Old Red Sandstone types of Europe. The American Devonian facies has already been referred to. On the eastern side of the ancient Archæan and Silurian ridge, which, stretching southwards from Canada, separated in early Palæozoic time the great interior basin from the Atlantic slopes, we find the Devonian rocks of New York, Pennsylvania, and the interior represented in New Brunswick and Nova Scotia by a totally different series of deposits. The contrast strikingly recalls that presented by the Old Red Sandstone of the north of Scotland and the Devonian rocks of North Germany. On the south side of the St. Lawrence the coast of Gaspé shows rocks of the Quebec group unconformably overlaid by grey limestones with green and red shales, attaining, according to Logan, a total thickness of about 2000 feet,[2] and in some bands replete with Upper Silurian fossils. They are conformably followed by a vast arenaceous series of deposits termed the Gaspé Sandstones, to which the careful measurements of Logan and his colleagues of the Canadian Geological Survey assign a depth of 7036 feet. This formation consists of grey and drab-coloured sandstones, with occasional grey shales and bands of massive conglomerate. Similar rocks reappear along the southern coast of New Brunswick, where they attain a depth of 9500 feet, and again on the opposite side of the Bay of Fundy. The researches of Dr. J. W. Dawson, already referred to, have made known the remarkable flora of these rocks. Some of the same plants have been met with in the Devonian rocks to the west of the Archæan ridge, so that there can be little doubt of the contemporaneity of the deposits on the two sides. Besides the abundant vegetation a few traces of the fauna of the period have been recovered from these Old Red Sandstones. Among them are the remains of several small crustaceans, including a minute, shrimp-like *Eurypterus*, and a more highly organized form named *Amphipeltis*. That the sea had at least occasional access to the inland basins into which the abundant terrestrial vegetation was washed is proved by the occurrence of marine organisms, such as a small annelid (*Spirorbis*) adhering to the leaves of the plants, and (in Gaspé and Nova Scotia) by the occasional appearance of brachiopods, especially *Lingula*, *Spirifera*, and *Chonetes*.[3]

Section IV.—Carboniferous.

§ 1. General Characters.

This great system of rocks has received its name from the seams of coal which form one of its distinguishing characters in most parts of the world. Both in Europe and America it may be seen passing down conformably into the Devonian and Old Red Sandstone. So

[1] Heer, *Q. J. Geol. Soc.* xxviii. 161. Dawson, *Op. cit.* xxix. 24.
[2] Geology of Canada, p. 393.
[3] Dawson's *Acadian Geology*, chaps. xxi. and xxii.

insensible indeed is the gradation in many consecutive sections where the two systems join each other that no sharp line can there be drawn between them. This stratigraphical passage is likewise in many places associated with a corresponding commingling of organic remains, either by the ascent of undoubted Devonian species into the lower parts of the Carboniferous series, or by the appearance in the upper Devonian beds of species which attained their maximum development in Carboniferous times. Hence there can be no doubt as to the true place of the Carboniferous system in the geological record. In some places, however, this system is found resting unconformably upon Devonian or older rocks, so that local disturbances of considerable magnitude occurred before or at the commencement of the Carboniferous period. It is deserving of notice that Carboniferous rocks are very generally arranged in basin-shaped areas. This disposition, so well seen in Europe, and particularly in the central and western half of the Continent, has in some cases been caused merely by the plication and subsequent extensive denudation of what were originally wide continuous sheets of rock, as may be observed in the British Isles. But the remarkable small scattered coal-basins of France and Central Germany were undoubtedly from the first isolated areas of deposit, though they have suffered, in some cases very greatly, from subsequent plication and denudation. In Russia and still more in China and Western North America, Carboniferous rocks cover thousands of square miles in horizontal or only very gently undulating sheets.

Rocks.—The materials of which the Carboniferous system is built up differ considerably in different regions; but two types of sedimentation have a wide development. In one of these, the marine type, limestones form the prevailing rocks, and are often visibly made up of organic remains, chiefly encrinites, corals, foraminifera, and molluscs. Sometimes these strata assume a compact homogeneous character, with black, grey, white, or mottled colours, when they are occasionally largely quarried as marble. Local developments of oolitic structure occur among them. They also assume in some places a yellowish dull finely granular aspect and more or less dolomitic composition. They occur in beds sometimes, as in Central England and Ireland, piled over each other for a depth of hundreds of feet, and in Utah for several thousand feet, with little or no intercalation of other material than limestone. The limestones frequently contain irregular nodules of a white, grey, or black flinty chert (phtanite), which, presenting a close resemblance to the flints of the chalk, occur in certain beds or layers of rock, sometimes in numbers sufficient to form of themselves tolerably distinct strata. These concretions are associated with the organisms of the rock, some of which, completely silicified and beautifully preserved, may be found imbedded in the chert. Dolomite, usually of a dull yellowish colour, granular texture, and rough feel, occurs both in beds regularly interstratified with the limestones and also in broad wall-like masses

running through the limestones. In the latter cases it is evident that the limestone has been changed into dolomite along lines of joint (p. 305); in the former, the dolomite may be due to contemporaneous alteration of the original calcareous deposit by the magnesian salts of sea-water in the manner already suggested (p. 305). Traced to a distance the limestones are often found to grow thinner, and to be separated by increasing thicknesses of shale, or to become more and more argillaceous and to pass eventually into shale. The shales, too, are often largely calcareous, and charged with fossils; but in some places, assume dark colours, become more thoroughly argillaceous, and contain, besides carbonaceous matter, an impregnation of pyrites or marcasite. Where the marine Carboniferous type dies out, the shales may become largely bituminous, passing even into coal, and being then associated with sandstones, clays, and ironstones.

The second type of sedimentation points to deposit in shallow lagoons, which at first were replenished from the sea, but afterwards appear to have been brackish and then fresh. Its most abundant strata are sandstones, which, presenting every gradation of fineness of grain up to pebbly grits, and even (near former shore-lines) conglomerates, are commonly yellow, grey, or white in colour, well-bedded, sometimes micaceous and fissile, sometimes compact; often full of streaks or layers of coaly matter. Next in abundance are the shales, commonly black and carbonaceous, frequently largely charged with pyritous impregnations, sometimes crowded with concretions of clay-ironstone. Coal occurs among these strata in seams varying from less than an inch up to several feet or yards in thickness, but swelling out in some rare examples to 100 feet or more. A coal-seam may consist entirely of one kind of coal. Frequently, however, it contains one or more thin layers or "partings" of shale, the nature or quality of the seam being alike or different on the two sides of the parting. The same seam may be a cannel-coal at one part of a mineral-field, an ordinary soft coal at a second, and an ironstone at a third. Moreover, each coal-seam is usually underlaid by a bed of fire-clay or shale, through which rootlets branch freely in all directions. These fire-clays, as their name denotes, are used for pottery or brick-making. They are the soil on which the plants of the coal grew, and it was doubtless the growth of the vegetation that deprived them of their alkalies and iron, and thus made them industrially valuable. Clay-ironstone occurs abundantly in some coal-fields both in the form of concretions (sphærosiderite) and also in distinct layers from less than an inch to eighteen inches or more in thickness. The nodules have generally been formed round some organic object such as a shell, seed-cone, fern-frond, &c. Many of the ironstone beds likewise abound in organic remains, some of them, like the "mussell-band" ironstone of Scotland, consisting almost wholly of valves of *Anthracosia* or other shell converted into carbonate of iron.

The mode of origin of coal cannot be closely paralleled by any modern formation. The nearest analogy is probably furnished by the

mangrove swamps alluded to already (p. 461). These masses of arborescent vegetation, with their roots spreading in salt water among marine organisms, grow out into the sea as a belt or fringe on low shores, and form a matted soil which adds to the breadth of the land. The earlier coal-growths no doubt also flourished in salt

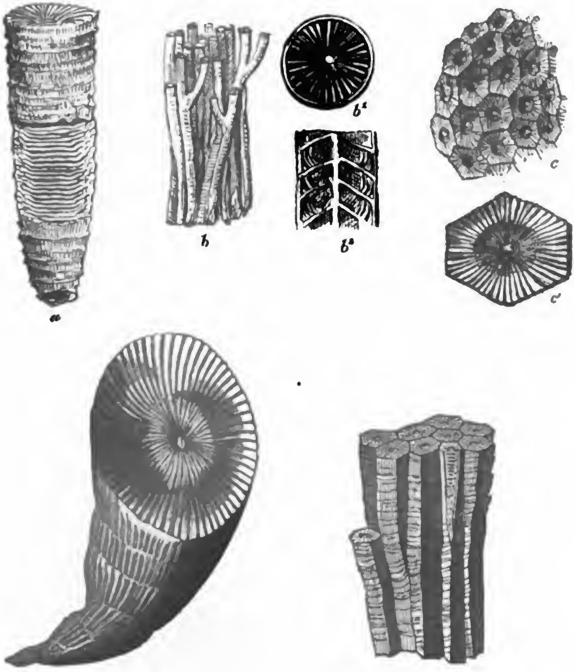


Fig. 334.—Carboniferous Corals.

a, Zaphrentis cylindrica (Scoul.); *b*, Lithostrotion junceum (Flem.), *b*¹, Do. magnified transverse section, *b*², Do. magnified longitudinal section; *c*, Lithostrotion Portlocki (Milne Edw.), *c*¹, Do. Calyx magnified; *d*, Cyathophyllum Stutchburyi (Milne Edw.): *e*, Lithostrotion basaltiforme (Phill.) sp.

water; for such shells as *Aviculopecten* and *Goniatites* are found lying on the coal or in the shales attached to it. Each coal-seam represents the accumulated growth of a period which was limited either by the exhaustion of the soil underneath the vegetation (as may be indicated by the composition of the fire-clays) or by the rate of the intermittent subsidence that affected the whole area of

coal-growths. From the fact that a succession of coal-seams, each representing a former surface of terrestrial vegetation, can be seen in a single coal-field extending through a vertical thickness of 10,000 feet or more, it is clear that the strata of such a field must have been laid down during prolonged and extensive subsidence. It has been assumed that besides depression, movements in an upward direction were needful to bring the submerged surfaces once more up within the limits of plant-growth. But this would involve a prolonged and almost inconceivable see-saw oscillation; and the assumption is really unnecessary if we suppose that the downward movement, though prolonged, was not continuous, but was marked by pauses, long enough for the silting up of lagoons and the spread of coal-jungles.

Life.—Each of the two phases of sedimentation just described has its own characteristic organic types, the one series of strata presenting us chiefly with the fauna of the sea, the other mainly with the flora of the land. The marine fauna is specially rich in crinoids, corals, and brachiopods, which of themselves constitute entire beds of limestone. Among the lower forms of life some genera of foraminifera have a wide extension; *Saccammina*, for example, forms beds of limestone in Britain, and *Fusulina* plays a still more important part in the Carboniferous Limestone of the region from Russia to China and Japan, as well as in North America, while *Nummulina* occurs in the Belgian limestones. The corals are represented in the English Carboniferous Limestone by some thirty genera, including about 100 species belonging to tabulate (*Favosites, Michelinia, Alveolites, Choetetes*), and still more to rugose forms (*Amplexus, Zaphrentis, Cyathophyllum, Aulophyllum, Clisiophyllum, Lithostrotion, Lonsdaleia, Phillipsastræa*). The Echinoderms are abundant and varied. Thus among the urchins of the Carboniferous seas were species of *Archæocidaris*, the plates and spines of which are of frequent occurrence. The blastoids or pentremites, which now took the place in the Carboniferous waters that in Silurian times had been filled by the Cystideans, attained their maximum development. But it was the order of crinoids that chiefly swarmed in the seas where the Carboniferous Limestone was laid down, their separated joints now mainly composing solid masses of rock many hundreds of feet in thickness. Among their most conspicuous genera were *Platycrinus, Cyathocrinus, Poteriocrinus, Rhodocrinus*, and *Gilbertsocrinus*. Tubicolar annelides abounded, some of the species being solitary and attached to shells, corals, &c., others occurring in small clusters, and some in gregarious

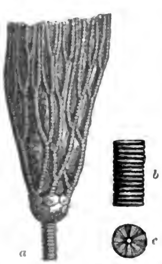


Fig. 335.—Carboniferous Crinoid.

Cyathocrinus planus (Miller); *a*, Calyx, arms and upper part of stem; *b*, portions of the stem; *c*, one of the column-joints showing central canal.

masses forming beds of limestone. The chief genera are *Spirorbis, Serpulites, Ortonia, Vermilia.*[1] Polyzoa abound in some portions of

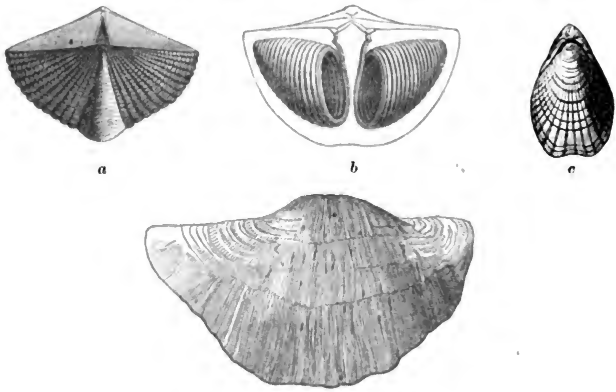


FIG. 336.—CARBONIFEROUS BRACHIOPOD.

a, Spirifera hysterica (Schloth.); *b*, Do. interior of dorsal valve, showing spiral calcareous supports for the arms; *c*, Terebratula hastata (Sow.); *d*, Productus giganteus (Martin).

the Carboniferous Limestone which were almost entirely composed of them, the genera *Fenestella, Sulcoretopora, Vincularia, Polypora, Diastopora,* and *Glauconome* being frequent. Of the brachiopods some of the most common forms are *Productus, Spirifera, Rhynchonella, Athyris, Chonetes, Orthis, Lingula,* and *Discina.*[2] But the higher molluscs now begin to preponderate over the brachiopods. The lamellibranchs in the English Carboniferous Limestone number 49 genera and 334 species, including forms of *Aviculopecten, Leda, Nucula, Sanguinolites, Leptodomus, Schizodus, Edmondia, Modiola,* and *Conocardium.* The gasteropods in the same rocks amount to 206 species belonging to 29 genera, among which *Euomphalus, Natica, Pleurotomaria, Macrocheilus,* and *Loxonema*

FIG. 337.—CARBONIFEROUS LAMELLIBRANCHS.

a, Conocardium aliforme (Goldf.); *b*, Aviculopecten sublobatus (Phill.), showing colour-bands.

[1] R. Etheridge, Jun., *Geol. Mag.* 1880, p. 110.

[2] *Productus* is almost wholly Carboniferous. Other genera had already existed a long time; some even of the species were of ancient date—*Orthis resupinata* of the Carboniferous Limestone and the Devonian *O. striatula* and *Strophomena depressa* had survived, according to Gosselet, from the time of the Bala beds of the Lower Silurian period. Gosselet *Esquisse*, p. 118.

are frequent. The genus *Bellerophon* is represented by 23 species, among which *B. Urei* and *B. decussatus* are frequent. The most abundant pteropod genus is *Conularia* (Fig. 339), which often attained a length of several inches. The cephalopods number in Britain 148 species, belonging among other genera to *Orthoceras*, *Nautilus*, *Discites*, and *Goniatites*.

The Crustacea present a facies very distinct from that of the

a b

Fig. 338.—Carboniferous Gasteropods.
a, Euomphalus pentangulatus (Sow.); *b*, Pleurotomaria carinata (Sow.), showing colour-bands.

previous Palæozoic formations. Trilobites now almost wholly disappear, only two or three genera of small forms (*Griffithides*, *Phillipsia*, *Brachymetopus*) being left. But other crustacea are abundant, especially ostracods (*Bairdia*, *Kirkbya*, *Leperditia*, *Beyrichia*), which crowd many of the shales and sometimes even form seams of limestone. A few macrura occur not infrequently, particularly *Anthrapalæmon* (Fig. 341), *Palæocrangon*, and *Palæocaris*, also several phyllopods (*Dithyrocaris*, *Ceratiocaris*, *Estheria*, *Leaia*) with the larger merostomatous *Eurypterus* and the king-crab *Prestwichia*.[1] The Carboniferous Limestone of the British Isles has supplied somewhere about 100 genera of fishes, chiefly represented by teeth and spines (*Psammodus*, *Cochliodus*, *Cladodus*, *Petalodus*, *Ctenodus*, *Rhizodus*, *Ctenoptychius*, &c.). Some of these were no doubt placoids which lived solely in the sea, but many, if not all, of the ganoids probably migrated between salt and fresh water; at least their remains are found in Scotland in strata full of land-plants, cyprids, and other indications of estuarine or fluviatile conditions.

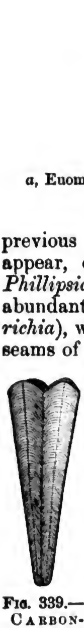


Fig. 339.—Carboniferous Pteropod. Conularia quadrisulcata.

The second phase of sedimentation, that of the coal-swamps, is marked by a very characteristic suite of organic remains. Most abundant of these are the plants, which possess a special interest inasmuch as they form the oldest terrestrial flora that has been abundantly preserved. This flora is

[1] Recent researches by Mr. B. N. Peach go to show that the Carboniferous *Eurypterus* was almost certainly a gigantic arachnid and not a crustacean. Some splendid specimens of its scorpion-like combs and feet have been obtained from the Lower Carboniferous rocks of the South of Scotland.

marked by a singular monotony of character all over the world, from the Equator into the Arctic Circle, the same genera and sometimes even the same species appearing to have ranged over the whole surface of

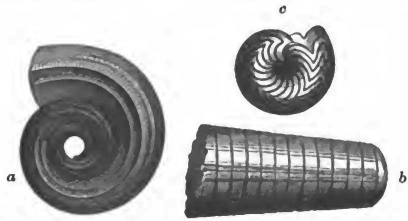


FIG. 340.—CARBONIFEROUS CEPHALOPODS.
a, Nautilus Koninckii (D'Orb.); *b*, Goniatites crenistria (Phill.); *c*, Orthoceras laterale (Phill.).

the globe. It consisted almost wholly of vascular cryptogams, and pre-eminently of Equisetaceæ, Lycopodiaceæ, and Ferns. Though referable to existing groups the plants presented many remarkable

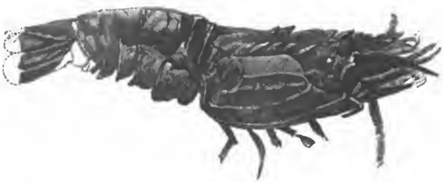


FIG. 341.—CARBONIFEROUS MACROUROUS CRUSTACEAN.
Anthrapalæmon Etheridgii (Peach), twice nat. size.

differences from their living representatives. In particular, save in the case of the ferns, they vastly exceeded in size any forms of the present vegetable world to which they can be assimilated. Our

FIG. 342.—CARBONIFEROUS ICHTHYODORULITE, OR DORSAL FISH-SPINE.
Ctenacanthus hybodoides (Egerton).

modern horse-tails had their allies in huge trees among the Carboniferous jungles, and the familiar club-moss of our hills, now a low creeping plant, was represented by tall-stemmed *Lepidodendra*

that rose fifty feet or more into the air. The ferns, however, present no such contrast to the forms still living. On the contrary, they often recall modern genera, which they resemble not merely in general aspect, but even in their circinnate vernation and fructification. With the exception of a few tree-ferns, they seem to have been all low-growing plants and perhaps were to some extent epiphytic upon the larger vegetation of the lagoons. Some of the

FIG. 343.—CARBONIFEROUS FISH.
Jaw of Rhizodus Hibberti (Ag.) sp., one-third nat. size.

more common genera are *Palæopteris, Sphenopteris, Neuropteris* (*Cyclopteris*), *Odontopteris, Pecopteris, Alethopteris.*

Among the Equisetaceæ, the genus *Calamites* is specially abundant. It usually occurs in fragments of jointed and finely-ribbed stems. From the rounded or blunted base of the stem other stems budded, and numerous rootlets proceeded, whereby the plants were anchored in the mud or sand of the lagoons, where they

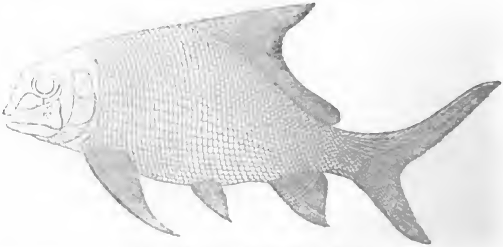


FIG. 344.—CARBONIFEROUS FISH.
Eurynotus crenatus (Ag.), "Cement-stones" of Scotland (after Traquair).

grew in dense thickets. To the foliage of Calamites different generic appellations have been attached (Fig. 347). The name *Asterophyllites* (*Calamocladus*) is given to jointed and fluted stems with verticils of slim branches proceeding from the joints and bearing whorls of long, narrow, pointed leaves. In *Sphenophyllum* the leaves were fewer in number and wedge-shaped; in *Annularia*, the close-set leaves were united at the base. *Calamodendron* is

FIG. 345.—CARBONIFEROUS FERN.
Sphenopteris affinis (Lindl. and Hutt.).

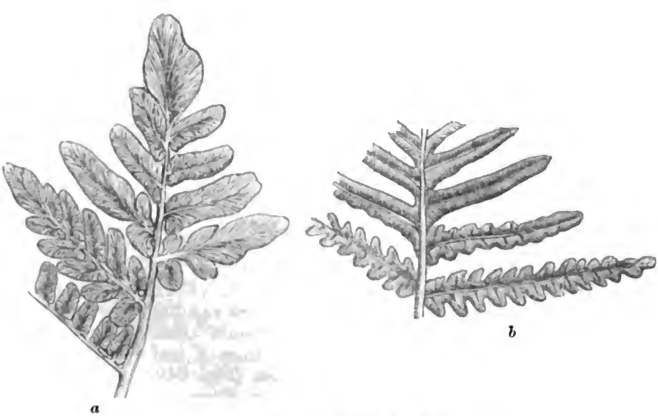


FIG. 346.—CARBONIFEROUS FERNS.
a, Neuropteris Loshii (Brongn.); *b*, Alethopteris Gibsoni (Lesq.).

believed by some botanists to be the cast of the pith of a woody stem belonging to some unknown tree, by others it is regarded as only a condition of the preservation of *Calamites*.

The Lycopods (Fig. 348) were represented by numerous species of the genus *Lepidodendron*, distinguished by the quincuncial leaf-scars on its dichotomous stem. Its branches, closely covered with pointed leaves, bore at their ends cones or spikes (*Lepidostrobus*) consisting of a central axis round which were placed imbricated scales each

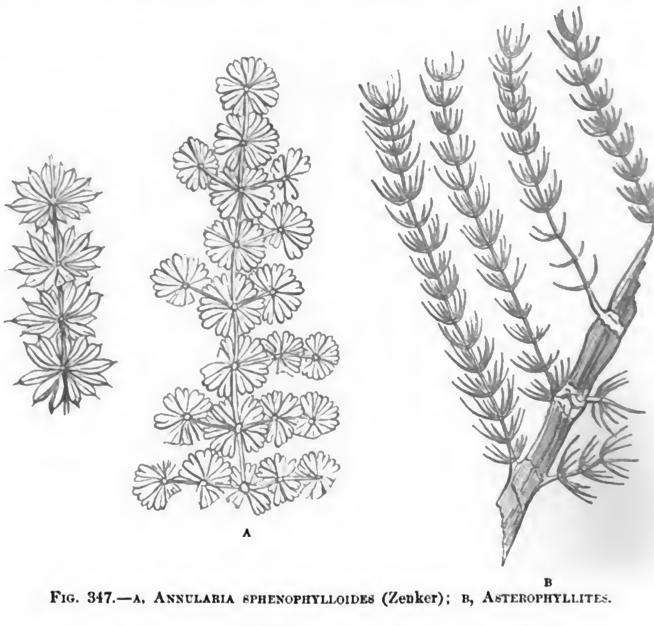
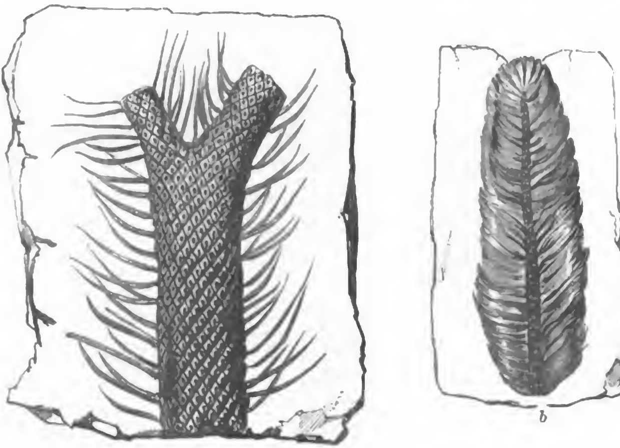


Fig. 347.—A, Annularia sphenophylloides (Zenker); B, Asterophyllites.

carrying a spore-case. Other conspicuous genera were *Ulodendron*, *Knorria*, *Lepidophloios*, *Halonia*, *Cyclocladia*.

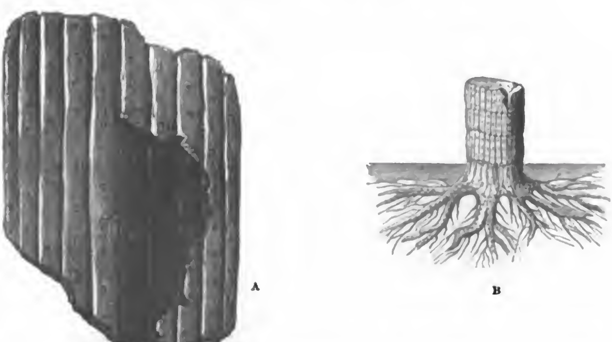
Among the most remarkable trees of the Carboniferous forests were the Sigillarioids. The genus *Sigillaria* was distinguished by the great height (fifty feet or more) of its trunk. Its stem was fluted, and marked by parallel perpendicular lines of leaf-scars, but as it grew, these external markings were lost (Fig. 349). The base of the stem passes into the roots known as *Stigmaria*, the pitted and tuberculed stems of which are such common fossils (Fig. 349, B, 350). There can be little doubt, however, that *Stigmaria* was a

type of root common to more than one kind of tree. The genus *Cordaites* attained a great profusion in the time of the Coal-measures.



b

FIG. 348.—CARBONIFEROUS LYCOPODS.
a, Lepidodendron (¼); *b*, Lepidostrobus, nat. size.



A B

FIG. 349.—A, SIGILLARIA; PORTION OF DECORTICATED STEM; B, SIGILLARIA STEM TERMINATING IN STIGMARIA ROOTS AND ROOTLETS.

It carried narrow or broad, parallel-veined leaves, somewhat like those of a Yucca, which were attached by broad bases at somewhat

wide distances to the stem, and on their fall left prominent leaf-scars. The true position of this plant is doubtful. It may have been

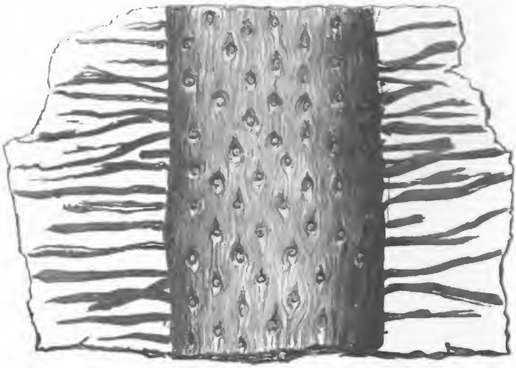


FIG. 350.—STIGMARIA WITH ATTACHED ROOTLETS.

lycopodiaceous; some botanists, however, have placed it with hesitation among the cycads, others have regarded it as a conifer. It bore spikes or buds known as *Carpolithes*. True Coniferæ were probably

FIG. 351.—CONIFEROUS TREE-TRUNK IMBEDDED IN SANDSTONE, CRAIGLEITH, EDINBURGH (AFTER WITHAM).

abundant on the drier ground, for their stems (*Dadoxylon*, *Araucarioxylon*, *Pinites*) have been met with, particularly in the tuffs of

ancient volcanic cones, on which they no doubt grew, and in sandstone, where they occur as drift-wood, perhaps from higher ground (Fig. 351). It should be remembered that the flora preserved in the Carboniferous rocks is essentially that of the low grounds and

FIG. 352.—ANTHOLITES WITH CARDIOCARPON.

swamps. Certain fruits known as *Antholithes* and *Cardiocarpon* (Fig. 352), occurring in great abundance in some bands of shale, have been regarded as of coniferous grade, but are now referred to the probably lycopodiaceous *Cordaites*. The fruit known as *Trigonocarpon*

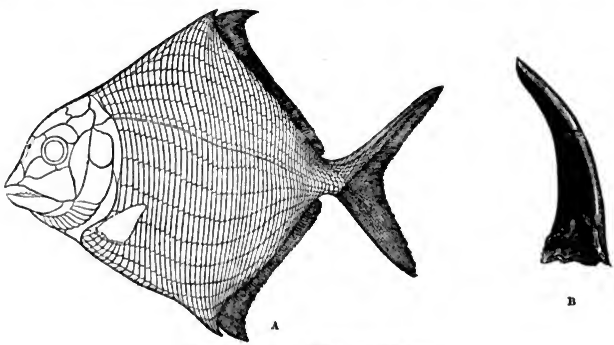


FIG. 353.—COAL MEASURE FISHES.
A, Cheirodus granulosus (Young), after Traquair; B, tooth of Strepsodus sauroides (Binney, sp.).

is supposed to be coniferous, somewhat like the fruit of the living *Salisburia*. That true monocotyledons existed even in the earlier part of the Carboniferous period, is proved by the discovery of a number of spikes, which have been referred to the living order of

Aroideæ (*Pothocites*), in the lower part of the Carboniferous system around Edinburgh.

The animal remains in the coal-bearing part of the Carboniferous rocks are comparatively few. As already stated, in certain bands of shale, coal, and ironstone in the lower half of the Coal-measures undoubted proofs of the presence of the sea are afforded by the occurrence of some of the familiar shells of the Carboniferous limestone. But towards the upper part of the Coal-measures, where these marine forms disappear, other lamellibranchs, that were probably denizens of brackish if not of fresh water, occur in abundance. Among the more frequent are *Anthracomya, Anthracosia*, and *Anthracoptera*. Crustaceans are chiefly represented by *Beyrichia* and *Estheria*, but large eurypterid forms likewise occur. Fishes are found frequently, remains of the larger kinds usually appearing in scales, teeth, fin-spines, or bones, while the smaller ganoids are often preserved entire.

Fig. 354.—Carboniferous Scorpion.
Eoscorpius glaber (B. N. Peach), Lower Carboniferous, Eskdale, Scotland.

Common genera are *Ctenodus, Strepsodus, Cheirodus* (Fig. 353), *Mesolepis, Ctenacanthus, Gyracanthus, Pleuracanthus, Ctenoptychius*.

The presence of true air-breathers among the jungles of the Carboniferous period has been established by the discovery of numerous specimens of arachnids, insects, and labyrinthodonts. Scorpions (*Eoscorpius*) have been found both in Europe and America, and recently have been obtained in great numbers, in excellent preservation, and of gigantic size in the Lower Carboniferous rocks of Scotland. Other arachnids occur, including ancient forms of spider (*Protolycosa*). Myriapods were represented by various millipedes (*Xylobius, Archiulus, Euphoberia*). True insects likewise flitted through these dense jungles, for the wings of a kind of May-fly (*Haplophlebium*), having a spread of fully seven inches, have been found in Canada, where too the oldest land-shell (*Pupa vetusta*) occurs. Several other genera of *Neuroptera* are known; also some

Orthoptera, including a form of cockroach (*Archimylacris*); some cricket-like forms (*Gryllacris*) and beetles. The wing of what has been supposed to be a moth has been found in the Belgian Coal-measures.[1] The British Carboniferous rocks have yielded 13 genera of labyrinthodonts (*Anthracosaurus, Loxomma, Ophiderpeton, Pholiderpeton, Pteroplax, Urocordylus*, &c.). These were probably fluviatile animals of predaceous habits, living on fish, crustacea, and other organisms of the fresh or salt waters of the coal lagoons. The larger forms are believed to have measured 7 or 8 feet in length; some of the smaller examples, though adult and perfect, do not exceed as many inches.[2]

Fossil plants have not hitherto served so well for purposes of geological classification as fossil animals (*ante*, p. 611). Nevertheless M. Grand'Eury, who has devoted so much time and labour to the investigation of the coal-basin of the Loire, believing that an undoubted order of succession of genera and species of plants can be determined, has subdivided the Carboniferous system into groups on this basis. The following is a summary of his arrangement:[3]

Supra-Carboniferous Flora, simpler and less rich than that below, showing a passage into the Permian flora above, characterized by a rapid diminution of *Alethopteris, Odontopteris xenopteroides, Dictyopteris, Annularia, Sphenophyllum.* The Calamites are represented by abundant individuals of *C. varians* and *C. Suckowii*, also *Asterophyllites equisetiformis;* the ferns by *Pecopteris cyatheoides, P. hemitelioides, Odontopteris minor, O. Schlotheimii*, several species of *Neuropteris*, &c.; the Sigillarias by *S. Brardii, S. spinulosa*, and *Stigmaria ficoides; Cordaites* by numerous narrow-leaved forms; the Calamodendra by a prodigious abundance of some species, e.g., *Calamodendron bistriatum, Calamites cruciatus, Arthropitus subcommunis;* the conifers by *Walchia piniformis* and some others.

Upper Coal Flora (properly so called). Calamites often abundant—*C. interruptus, C. Suckowii, C. cannæformis, Asterophyllites hippuroides, Macrostachya infundibuliformis* (very common), *Annularia brevifolia*, and *A. longifolia* (common throughout), *Sphenophyllum oblongifolium.* Ferns richly developed, particularly of the genera *Pecopteris* (*P. unita, arguta, polymorpha*, and especially *Schlotheimii*); *Odontopteris* (*O. reichiana, Brardii, mixoneura, xenopteroides*, the last extremely abundant); *Caulopteris macrodiscus, Alethopteris Grandini* in great profusion, *Callipteridium* (*C. ovatum, gigas, densifolia*, common). Lepidodendra have almost disappeared; Sigillariæ are not uncommon (*S. rhitydolepis, S. Brardii*), with *Stigmariopsis* and *Syringodendron. Cordaites* occurs in great abundance; the conifers are represented by *Walchia pinniformis* and a few other species. Calamodendra occur in great abundance, especially *Calamites cruciatus.*

Upper Coal Flora—Lower zone (*Flore du terrain houiller sous-supérieure*).—Calamites and Asterophyllites abundant in individuals and species (*C. Suckowii, Cistii, cannæformis, varians, approximatus, A. rigidus,*

[1] See an interesting paper on Carboniferous insects by Dr. H. Woodward (*Q. J. Geol. Soc.* 1872, p. 60), where a list is given of 6 species of myriapods, 3 coleoptera, 13 orthoptera, and 17 neuroptera, from the Coal-measures.

[2] Miall, *Brit. Assoc.* 1873, 1874.

[3] "Flore Carbonifère du Département de la Loire et du Centre de la France," Cyrille Grand'Eury, Paris, 1877.

grandis, hippuroides), *Annularia radiata, Sphenophyllum*. Among the ferns there are few true sphenopterids, but *Neuropteris* is common (*N. flexuosa, auriculata*), also *Odontopteris* (*O. reichiana, Schlotheimii*), *Pecopteris* (*P. arborescens, pulchra, candolliana, villosa, oreopteridia, crenulata, aspidoides, elegans*), *Caulopteris, Psaronius*. Lepidodendra are few (*L. Sternbergii, elegans, Lepidostrobus sub-variabilis, Lepidophloios laricinus, Knorria Selloni, Lepidophyllum majus*). Sigillarioid forms are likewise on the wane when compared with their profusion below (*Sigillaria elliptica, Candollii, tessellata, elegans, Grasiana, Brardii, spinulosa; Syringodendron cyclostigma, distans; Stigmaria ficoides* abundant). Cordaites, however, now becomes the dominant group of plants, but with a somewhat different facies from that which it presents in the middle Coal-measures (*C. borassifolius, C. principalis, Dadoxylon Brandlingii, Cardiocarpon emarginatum, Gutbieri, majus, ovatum*). *Calamites cruciatus* makes its appearance, also *Walchia pinniformis*.

Middle Coal Flora—Upper Zone (*supra-moyenne*).—Calamites numerous (*C. Suckowii, Cistii, cannæformis, ramosus; Asterophyllites foliosus, longifolius, grandis, rigidus; Annularia minuta, brevifolia; Sphenophyllum saxifragæfolium, Schlotheimii, truncatum, majus*). Ferns represented by *Sphenopteris* (*S. latifolia, irregularis, trifoliolata, cristata*, &c.), *Prepecopteris* (maximum of this *genus*), *Pecopteris* (*P. abbreviata, villosa, Cistii, oreopteridia*, &c.), *Caulopteris, Neuropteris*, and other genera. Lepidodendra are not infrequent (*Lepidodendron aculeatum, Sternbergii, elegans, rimosum; Lepidostrobus variabilis; Lepidophloios laricinus, Lepidophyllum majus*), and various *Lycopodites*. The proportion of *Sigillaria* is always large (*S. Cortei, intermedia, Sillimanni, tessellata, cyclostigma, alternans, Brongniarti, Stigmaria ficoides, minor*). *Pseudosigillaria* is abundant, especially *P. monostigma*. *Cordaites* appears in some places abundantly (*C. borassifolius, Artisia transversa, Cladiscus Schnorrianus*), and its fruits are numerous and varied (*Cardiocarpon emarginatum, orbiculare, ovatum*).

Middle Coal Flora (properly so-called), characterized above all by the dominant place of the Sigillarioids, which now surpass the lepidodendroids and form the main mass of the coal seams. The genus *Sigillaria* here attains its maximum development (*S. Groeseri, angusta, scutellata, intermedia, elongata, notata, alternans, rugosa, reniformis, leopoldina*, and many more; *Pseudosigillaria striata, rimosa, monostigma; Stigmaria ficoides, minor*). Lepidodendroids are large and frequent (*Lepidodendron aculeatum, obovatum, caudatum, rimosum, Sternbergii, elegans; Lepidophloios laricinus; Ulodendron majus, minus; Halonia tuberculata, tortuosa, regularis; Lepidophyllum majus; Lepidostrobus variabilis*). The ferns are abundant and varied; the Sphenopterids include many species, of which *Sphenopteris Hoeninghausii* and *tenella* are common (also *S. Bronni, Schlotheimii, tenuifolia, rigida, furcata, elegans*); *Alethopteris* is very plentiful (*A. lonchitica, Serlii, Mantelli, heterophylla*); also *Lonchopteris Bricii* and *L. Röhlii; Prepecopteris, Pecopteris, Megaphyton, Neuropteris* (*N. flexuosa, Loshii, tenuifolia, gigantea*), *Cyclopteris, Aulacopteris*. The calamites are widely diffused and abundant, especially *Calamites dubius, undulatus, ramosus, decoratus, Steinhaueri; Asterophyllites subhippuroides, grandis, longifolius; Volkmannia Binneyana; Sphenophyllum* seems here to reach its maximum, characteristic species being *S. emarginatum, saxifragæfolium, erosum, dentatum, truncatum, Schlotheimii*. Some coals and shales abound with *Cardiocarpon*, also *Trigonocarpon*, and *Nöggerathia*.

Middle Coal Flora.—Lower zone (*Flore houillère sous-moyenne*). Lepidodendroids are characteristically abundant and varied (*Lepidodendron aculeatum, obovatum, crenatum, Haidingeri, undulatum, longifolium;* and *Lepidophloios laricinus, intermedius, crassicaulis; Ulodendron*, abundant in England, *U. dichotomum, punctatum, majus, minus*, &c.; *Halonia tortuosa, regularis*, &c.). Sigillarioids are numerous (*Sigillaria oculata, elegans, scutellata, elongata, mammillaris, alveolaris, reniformis; Stigmaria ficoides, minor, stellata, reticulata; Dictyoxylon, Lyginodendron*). Calamites abound (*Calamites cannæformis, Suckowii, Cistii, decoratus, approximatus; Asterophyllites subhippuroides, longifolius; Volkmannia polystachya*). Ferns likewise form a notable part of the flora, especially sphenopterids (*Sphenopteris latifolia, acutifolia, elegans, dissecta, furcata, Gravenhorstii, nervosa, muricata, obtusiloba, trifoliata*); also *Prepecopteris Silesiaca, oxyphylla, Glockeri, dentata; Megaphyton majus; Pecopteris ophiodermatica* and other similar forms. The neuropterids become abundant (*Neuropteris heterophylla, Loshii, gigantea, tenuifolia; Cyclopteris obliqua; Alethopteris lonchitica*, &c.). The abundant *Cordaites* of the higher measures are absent, though the fruit *Carpolithes* occasionally occurs.

Infra Coal-Measure Flora.—(Millstone grit, *l'étage infra-houiller*), characterized essentially by lepidodendroids and stigmarias. *Lepidodendron aculeatum, obovatum, crenatum, brevifolium, caudatum, carinatum, rimosum, Volkmannianum; Ulodendron punctatum, ellipticum, majus; Halonia tuberculosa; Lepidophloios intermedius, laricinus. Sigillaria* is not very common, but *S. oculata, alveolata* (Stern), *Knorrii, trigona, minima*, and other species occur. The ferns are more varied than in older parts of the system, sphenopterids being the dominant types (*Sphenopteris distans, elegans, tridactylites, furcata, dissecta, rigida, divaricata, linearis, acutiloba*, &c.). The genus *Pecopteris* is represented by a few species. *Neuropteris* is comparatively rare (*N. Loshii, tenuifolia*) *Alethopteris* appears in the widespread species *A. lonchitica*, and a few others. Calamites are not relatively abundant (*Calamites undulatus, Steinhaueri, communis, cannæformis, Cistii; Asterophyllites foliosus*, &c.).

Flora of the Upper Greywacke.—Lepidodendroids are the prevalent forms (*Lepidodendron carinatum, polyphyllum, volkmannianum, rugosum, caudatum, aculeatum, obovatum; Halonia tetrasticha, regularis; Ulodendron ovale, commutatum*). *Stigmaria* in several species occurs, sometimes abundantly; but *Sigillaria* is rare (*S. undulata, Volzii, costata, subelegans, venosa, Guerangeri, verneuillana*). Calamites are not infrequent (*C. Roemeri, Volzii, cannæformis*, &c.). The ferns are chiefly sphenopterids (*Sphenopteris dissecta, elegans, Gersdorfii, distans, tridactylites, schistorum; Cyclopteris tenuifolia, Haidingeri, flabellata, Prepecopteris aspera, subdentata; Neuropteris heterophylla, Loshii*).

Flora of the Culm, characterized by the abundance of lepidodendroids of the type of *L. veltheimianum* (with *Knorria imbricata*), by the number of *Bornia transitionis*, associated with *Calamites Roemeri, Stigmaria ficoides* (and other species), and by the abundance of the palæopterid ferns (*Palæopteris Machaneti, antiqua, dissecta*, (*Sphenopteris*) *affinis* (Fig. 345); *Cardiopteris frondosa; Rhodea divaricata, elegans, moravica; Sphenopteris Göpperti, Schimperi*, &c.).

Carboniferous Limestone Flora.—The palæopterid ferns reach a maximum (*Palæopteris inæquilatera, Lindseæformis, polymorpha, frondosa*). Sphenopterid forms are found in *Sphenopteris bifida, lanceolata,*

confertifolia. The old genus *Cyclostigma* here disappears (*C. minuta*, *Nathorstii*). The more characteristic lepidodendroids are *Lepidodendron weikianum*, *veltheimianum*, *squamosum*; *Knorria imbricata*, *acicularis*. The flora includes also *Stigmaria ficoides*, *rugosa*; *Bornia transitionis*: *Asterophyllites elegans*, &c.

§ 2. Local Development.

The European development of the Carboniferous system presents certain well-marked local types which bring clearly before the mind some of the geographical features, as well as the succession of geological changes. During the earlier half of the Carboniferous period there still lay much land towards the north and north-west, whence a continuous supply of sandy and muddy sediment was derived. A sea of moderate depth and clear water extended from the Atlantic across the site of Central Ireland, the heart of England, and Belgium into Westphalia. The southern margin of this ancient Mediterranean was probably formed by the ridge of older Palæozoic and crystalline rocks, which, extending from the west of England into the Boulonnais, and from Brittany into Central France, sweeps eastward by the uplands of the Ardennes, Hundsruck, Taunus, and Thuringer Wald into Saxony and Silesia. In the deeper and clearer water massive beds of limestone accumulated; but towards the land, at least on the north side of the sea, there was an increasingly abundant deposit of sand and mud, with occasional seams of coal and sheets of limestone. The whole region underwent slow subsidence and infilling of sediment, until at last vast marshes and jungles occupied tracts that had been previously sea. By degrees the lower parts of the surrounding land were likewise submerged beneath the accumulating coal-growths, which consequently spread over the sinking areas. Hence while across the central portions of the Carboniferous region the normal succession of strata presents a lower marine division consisting mainly of limestone, and an upper brackish-water division composed of sandstones, shales, and coal seams, the marginal tracts show hardly any limestone, some of them indeed, as in Central France, containing only the very highest part of the upper division.

The British Isles.[1]—This general sequence is well illustrated in the structure of the Carboniferous rocks of Britain—an area sufficiently extensive to contain more than one type of the system, and thus to cast interesting light on the varied geographical conditions under which the rocks were accumulated. As the land whence the chief supplies of sediment were derived rose mainly to the north and north-west, while the centre of England and Ireland lay under clear water of moderate depth, the sea shallowed northwards into Scotland, and its bottom was covered with constantly accumulating banks of sand and sheets of mud. Hence vertical sections of the Carboniferous system of Britain differ greatly according to the districts in which they are taken. The subjoined table may be regarded as expressing the typical

[1] Detailed information regarding British Carboniferous rocks will be found in the *Memoirs of the Geological Survey*. See also Phillips' "Geology of Yorkshire," Hull's "Coal Fields of Great Britain," and papers by Prestwich (*Geol. Trans.* 2nd ser. v.), Sedgwick (*Op. cit.* ix., *Q. J. Geol. Soc.* viii., *Proc. Geol. Soc.* ii.), Binney (*Q. J. Geol. Soc.* ii. xviii.), Kirkby (*Op. cit.* xxxvi.). Green and Russell, "Geology of Yorkshire Coalfield" in *Mem. Geol. Surv.*

subdivisions which can be recognized, with modifications, in all parts of the country:

Coal-measures	Red and grey sandstones, clays, and sometimes breccias, with occasional seams and streaks of coal and Spirorbis limestone (*Cythere inflata*, *Spirorbis carbonarius*).
	Middle or chief coal-bearing series of yellow sandstones, clays, and shales, with numerous workable coals (*Anthracosia*, *Anthracomya*, *Beyrichia*, *Estheria*, *Spirorbis*, &c.).
	Gannister beds, flagstones, shales, and thin coals, with hard siliceous (gannister) pavements (*Orthoceras*, *Goniatites*, *Posidonia*, *Aviculopecten*, *Lingula*, &c.).
Millstone Grit	Grits, flagstones, and shales, with thin seams of coal.
Carboniferous Limestone series	Yoredale group of shales and grits passing down into dark shales and limestones (*Goniatites*, *Aviculopecten*, *Posidonomya*, *Lingula*, *Discina*, &c.).
	Thick (Scaur or Main) limestone in south and centre of England and Ireland, passing northwards into sandstones, shales, and coals (abundant corals, polyzoans, brachiopods, lamellibranchs, &c.).
	Lower Limestone Shale of south and centre of England (marine fossils like those of overlying limestone). The Calciferous Sandstone group of Scotland (marine, estuarine, and terrestrial organisms), represents the Lower Limestone Shale and lower part of the English Mountain Limestone, and graduates downward insensibly into the Upper Old Red Sandstone.

Carboniferous Limestone series and local equivalents.—In the south-west of England, and in South Wales, the Carboniferous system passes down conformably into the Old Red Sandstone. The passage beds consist of yellow, green, and reddish sandstones, green, grey, red, blue, and variegated marls and shales, sometimes full of terrestrial plants. They are well exposed on the Pembrokeshire coasts, marine fossils being there found even among the argillaceous beds at the top of the Red Sandstone series. They occur with a thickness of about 500 feet in the gorge of the Avon near Bristol, but show less than half that depth about the Forest of Dean. At their base there lies a bone-bed containing abundant palatal teeth. Not far above this horizon plant-bearing strata are found. Hence these rocks bring before us a mingling of terrestrial and marine conditions. In Yorkshire, near Lowther Castle, Brough, and in Ravenstonedale, alternations of red sandstones, shales, and clays, containing *Stigmaria* and other plants, occur in the lower part of the Carboniferous Limestone. Along the eastern edge of the Silurian hills of the Lake district, what is commonly regarded as the Old Red Sandstone appears here and there, and passes up through a succession of red and grey sandstones, and green and red shales and marls with plants, into the base of the Carboniferous Limestone. It is highly probable, however, that these red strata occur on many successive horizons; so that they should be regarded not as marking any particular period, so much as indicating the recurrence of certain peculiar littoral conditions of deposit (p. 717).

In the south and south-west of England, and in South Wales, the base of the Carboniferous system consists of certain dark shales known as Lower Limestone Shale, in which a few characteristic fossils of the Carboniferous Limestone occur. These basement beds vary up to rather more than 400 feet in thickness. They are overlaid conformably by the thick mass of limestone, which in Britain and Belgium forms a most characteristic member of the Carboniferous system.

On referring to a geological map of England it will be seen that from

Northumberland southwards to the low plains in the centre of England there runs a ridge of high ground, formed by a great anticline, along which the Carboniferous Limestone appears at intervals from underneath higher members of the system. In this northern Carboniferous area, of which the axis is known as the Pennine Chain, the limestone attains its greatest development. In one portion of the district it reaches a depth of 4000 feet, and yet its actual base is nowhere seen. This Pennine region appears to have been the area of maximum depression during the early part of the Carboniferous period in Britain. Traced towards the south-west, the limestone diminishes to sometimes not more than 500 feet in South Wales. Northwards, losing its character as a massive calcareous formation, it is split up by intercalations of sandstone, shale, coal, &c., until actual limestone becomes a very subordinate member of the series in central Scotland.

Where typically developed, the Carboniferous Limestone is a massive well-bedded limestone, chiefly light bluish-grey in colour, varying from a compact homogeneous to a distinctly crystalline texture, and rising into ranges of hills, whence its original name "Mountain Limestone." It contains occasional scattered irregular nodules and nodular beds of dark chert (phtanite). Though it is abundantly fossiliferous, little has yet been done in working out in detail the successive life-zones of this great mass of rock, as has been done so well for the corresponding limestone series of Belgium. The fossils commonly stand out on weathered surfaces of the rock, but microscopic investigation shows that even those portions of the mass which appear most structureless consist of the crowded remains of marine organisms. The limestone may be regarded as derived almost entirely from the organic debris of a sea-floor. Diversities of colour and lithological character occur, whereby the bedding of the thick calcareous mass can be distinctly seen. Here and there a more marked crystalline structure has been superinduced; while along lines of principal joints the rock on either side for a breadth of 20 or 30 fathoms is converted into yellowish or brown dolomite or "dunstone" (see p. 305). In Derbyshire, sheets of contemporaneous lava, locally termed "toadstone," are interpolated in the Carboniferous Limestone. Other evidences of contemporaneous volcanic action have been noted by Mr. J. Horne in the Isle of Man, but it is in Scotland, as will be immediately referred to, that the most remarkable proofs of abundantly active Carboniferous volcanoes have been preserved.

In the Carboniferous areas of the south-west of England and South Wales, the limits of the Carboniferous Limestone are well defined by the Limestone Shale below, and by the Farewell Rock or Millstone Grit above. In the Pennine area, however, the massive limestone is succeeded by a series of shales, limestones, and sandstones, known as the Yoredale group. These cover a large area and attain a great thickness. In North Staffordshire they are 2300 feet thick, which, added to the 4000 feet of limestone below, gives a depth of 6300 feet for the whole Carboniferous Limestone series of that region. In Lancashire the Yoredale rocks attain still more stupendous dimensions, Mr. Hull having found them to be no less than 4500 feet thick. Both the lower or main (Scaur) limestone and the Yoredale group pass northwards into sandstones and shales, with coal-seams, and diminish in thickness.

Traced northwards into Scotland the Carboniferous Limestone undergoes a remarkable petrographical and palæontological change. Its

massive limestones dwindle down and are replaced by thick courses of yellow and white sandstone, dark shale, and seams of coal and ironstone, among which only a few thin sheets of limestone are to be met with. Scottish geologists have divided the lower half of their Carboniferous system into two well-marked series—the Calciferous Sandstones and the Carboniferous Limestone. The Calciferous Sandstone series is composed of two groups of strata—the lower of which or Red Sandstone group consists of red, white, and yellow sandstones, blue, grey, green, and red marls or clays, while the upper or Cement-stone group is made up of white and yellow sandstones, blue and black shales, thin coals, seams of limestone and cement-stone, and abundant volcanic rocks. The red sandstones pass down into the Upper Old Red Sandstone, with which indeed they might be classed, and from which they differ merely in the less intensity of their colour, in the frequent grey and purplish tints they assume, and in the absence of the deep brick-red marls so marked in the Upper Old Red Sandstone. In the west of Scotland, as above (p. 716) stated, there occur among the red sandstones (some of which contain Upper Old Red Sandstone fishes) bands of limestone full of true Carboniferous Limestone corals and brachiopods. Hence it is evident that the Carboniferous Limestone fauna had already appeared outside the British area before the final cessation of the peculiar conditions of sedimentation of the Old Red Sandstone period. It was not however until these conditions had disappeared that the sea began to invade the lakes and creep over the sinking land of this part of Britain, and to bring with it the abundant Carboniferous fauna. The Calciferous Sandstones of Scotland represent a phase of sedimentation contemporaneous with the deposition of the Lower Limestone Shale and lower portion of the Carboniferous Limestone of England.

One of the most singular features of the Lower Carboniferous rocks of Scotland is the prodigious abundance of the intercalated volcanic rocks. So varied indeed are the characters of these masses and so manifold and interesting is the light they throw upon volcanic action that the region may be studied as a typical one for this class of phenomena. (See Book IV. Part vii. Sect. i.) Sections are abundant inland on the sides of the hills and in the stream-courses, while along the sea-shore the rocks have been admirably exposed. The most persistent zone of volcanic rocks in the whole of the Scottish Carboniferous series is that which succeeds the lower or red sandstone group of the Calciferous Sandstones. Composed of successive sheets of porphyrites and tuffs, it sweeps in long isolated ranges of hills from Arran and Bute on the west to the mouth of the estuary of the Forth on the east, and from the Campsie Fells on the north to the heights of Ayrshire and still further south in Berwickshire, Liddesdale, and the English border. These volcanic sheets sometimes reach a thickness of 1500 feet. That they belong to the Carboniferous system is shown by the occurrence of shales and sandstones (with Carboniferous plants) at their base. They show that the early part of the Carboniferous period in Scotland was marked by a prodigious volcanic activity, followed by the prolonged subsidence required for the accumulation of the Carboniferous system.

Above this volcanic zone lies the Cement-stone group or upper subdivision of the Calciferous sandstones. In Berwickshire and the west of Scotland it consists of thin-bedded white, yellow, and green sandstones, grey, green, blue, and red clays and shales, with thin bands of pale

argillaceous limestone or cement-stone. Seams of gypsum occasionally appear. These strata are, on the whole, singularly barren of organic remains. They seem to have been laid down with great slowness, and without disturbance, in enclosed basins, which were not well fitted for the support of animal life, though fragmentary plants serve to show that the adjoining slopes were covered with vegetation. In the basin of the Firth of Forth, however, the group presents a different lithological aspect and is abundantly fossiliferous. It there usually consists of yellow, grey, and white sandstones, with blue and black shales, clay-ironstones, limestones, "cement-stones," and occasional seams of coal. The sandstones form excellent building stones, the city of Edinburgh having been built of them. Some of the shales are so bituminous as to yield, on distillation, from 30 to 40 gallons of crude petroleum to the ton of shale; they are consequently largely worked for the manufacture of mineral oils. The limestones are usually dull, yellow, and close-grained, in seams seldom more than a few inches thick, and graduate by addition of carbonate of iron into cement-stone; but occasionally they swell out into thick lenticular masses like the well-known limestone of Burdie House, so long noted for its remarkable fossil fishes. This limestone appears to be mainly made of the crowded cases of a small ostracod crustacean (*Leperditia Okeni*, var. *Scoto-Burdigalensis*). The coal-seams are few and commonly too thin to be workable, though one of them, known as the Houston coal, has been mined to some extent in Linlithgowshire. The fossils of the cement-stone group indicate an alternation of fresh or brackish water and marine conditions. They include numerous plants, of which the most abundant are *Sphenopteris affinis* (Fig. 345), *Lepidodendron* (two or three species), *Lepidostrobus variabilis* (Fig. 348, *b*), *Araucarioxylon*. Some of the shales near Edinburgh have afforded a few specimens of a true monocotyledon allied to the modern Pothos (*Pothocites Grantoni*). Ostracod crustaceans, chiefly the *Leperditia* above mentioned, crowd many of the shales. With these are usually associated abundant traces of the presence of fish, either in the form of coprolites, or of scales, bones, plates, and teeth. The following are characteristic species: *Elonichthys striolatus*, *E. Robisoni*, *Rhadinichthys ornatissimus*, *Nematoptychius Greenockii*, *Eurynotus crenatus* (Fig. 344), *Rhizodus Hibberti*, *Megalichthys* sp., *Gyracanthus tuberculatus*, *Ctenoptychius pectinatus*. At intervals throughout the group marine horizons occur, usually as shale bands marked by the presence of such distinctively Carboniferous Limestone species as *Spirorbis carbonarius*, *Discina nitida*, *Lingula squamiformis*, *Bellerophon decussatus*, and *Orthoceras cylindraceum*.

The Cement-stone group of the basin of the Firth of Forth contains a great number and variety of associated volcanic masses. At the time when it was accumulating, the region of shallow lagoons, islets, and coal-growths was dotted over with innumerable active volcanic vents. The eruptions continued into the time of the Carboniferous Limestone, but ceased before the deposition of the Millstone Grit. The lavas are chiefly varieties of basalt-rocks, sometimes coarsely crystalline and even granitoid in texture, and graduating through intermediate stages to true close-grained compact basalts, which neither externally nor in microscopic structure differ from basalt of Tertiary date. Among them also are felsites and porphyrites. The tuffs present many varieties, one of the most interesting being an ancient form of palagonite-tuff.[1]

The Carboniferous Limestone series of Scottish geologists, probably

[1] See *Trans. Roy. Soc. Edin.* xxix. p. 437, and *ante*, p. 547, *et seq.*

representing the upper part of the typical formation in Central England, consists mainly of sandstones, shales, fire-clays, and coal-seams, with a few comparatively thin seams of encrinal limestone. The thickest of these limestones, known as the Hurlet or Main limestone, is usually about 6 feet in thickness, but in the north of Ayrshire swells out to 100 feet, which is the most massive bed of limestone in any part of the Scottish Carboniferous system. One of a group of limestone beds at the base of the series, it lies upon a seam of coal, and is in some places associated with pyritous shales, which have been largely worked as a source of alum. This superposition of a bed of marine limestone on a seam of coal is of frequent occurrence in Scotland. Above these lower limestones comes a thick mass of strata containing many valuable coal-seams and ironstones (Lower or Edge Coals). Some of these strata are full of terrestrial plants (*Lepidodendron*, *Sigillaria*, *Stigmaria*, *Sphenopteris*, *Alethopteris*); others, particularly the ironstones, contain marine shells, such as *Lingula*, *Discina*, *Leda*, *Myalina*, *Euomphalus*. Numerous remains of fishes have been obtained, more especially from some of the ironstones and coals (*Gyracanthus formosus* and other placoid fin-spines, *Megalichthys Hibberti*, *Rhizodus Hibberti*, with species of *Elonichthys*, *Acanthodes*, *Ctenoptychius*, &c.). Remains of labyrinthodonts have also been found in this group of strata, and have been detected even down in the Burdie House limestone. The highest division of the Scottish Carboniferous Limestone series consists of a group of sandstones and shales, with a few coal-seams, and three, sometimes more, bands of marine limestone. Although these limestones are each seldom more than 3 or 4 feet thick, they have a wonderful persistence throughout the coal-fields of central Scotland. As already mentioned (p. 492), they can be traced over an area of at least 1000 square miles, and they probably extended originally over a considerably greater region. The Hurlet limestone with its underlying coal can also be followed across a similar extent of country. Hence it is evident that during certain epochs of the Carboniferous period a singular uniformity of conditions prevailed over a large region of deposit in the centre of Scotland.

The difference between the lithological characters of the Carboniferous Limestone series, in its typical development, as a great marine formation, and in its arenaceous and argillaceous prolongation into the north of England and Scotland, has long been a familiar example of the nature and application of the evidence furnished by strata as to former geographical conditions. It shows that the deeper and clearer water of the Carboniferous sea spread over the site of Yorkshire, Derbyshire, and Lancashire; that the land lay to the north, and that, while the whole area was undergoing subsidence, the maximum movement took place over the area of deeper water. The sediment derived from the north during the time of the Carboniferous Limestone seems to have sunk to the bottom before it could reach the great basin in which foraminifers, corals, crinoids, and molluscs were building up the thick calcareous deposit. Yet the thin limestone bands, which run so persistently among the Lower Carboniferous rocks in Scotland, prove that there were occasional episodes during which the sediment ceased to arrive, and when the same species of shells, corals, and crinoids spread northwards towards the land, forming for a time over the sea-bottom a continuous sheet of calcareous ooze like that of the deeper water further south. These intervals of limestone growth no doubt point to times of more rapid submergence, perhaps also

to other geographical changes whereby the sediment was for a time prevented from spreading so far.

Viewed as a whole, therefore, the Carboniferous Limestone series of the northern part of the British area contains the records of a long-continued but intermittent process of subsidence. The numerous coal-seams with their under-clays were undoubtedly surfaces of vegetation that grew in luxuriance on the wide marine mud-flats, and mark pauses in the subsidence. Perhaps we may infer the relative length of these pauses from the comparative thicknesses of the coal-seams. The overlying and intervening sandstones and shales indicate a renewal of the downward movement, and the gradual infilling of the depressed area with sediment, until the water once more shoaled, and the vegetation from adjacent swamps spread over the muddy flats as before. The occasional limestones serve to mark epochs of more prolonged or more rapid subsidence, when marine life was enabled to flourish over the site of the submerged forests. But that the sea, even though tenanted in these northern parts by a limestone-making fauna, was not so clear and well suited for the development of animal life during some of these submergences as it was further south, seems to be proved by the paucity and dwarfed forms of the fossils in the thin limestones, as well as by the admixture of clay in the stone.

Ireland presents a development of Carboniferous rocks, which on the whole follows tolerably closely that of the sister island. In the northern counties the lowest members are evidently a prolongation of the type of the Scottish Calciferous Sandstones. In the southern districts, however, a very distinct and peculiar facies of Lower Carboniferous rocks is to be remarked. Between the top of the Old Red Sandstone and the base of the Carboniferous Limestone there occurs in the county of Cork an enormous mass (fully 5000 feet) of black and dark-grey shales, impure limestones, and grey and green grits and true cleaved slates. To these rocks the name of Carboniferous Slate was given by Griffith. They contain numerous Carboniferous Limestone species of brachiopods, echinoderms, &c., as well as traces of land-plants in the grit bands. Great though their thickness is in Cork, they rapidly change their lithological character, and diminish in mass as they are traced away from that district. In the almost incredibly short space of 15 miles, the whole of the 5000 feet of Carboniferous Slate of Bantry Bay seems to have disappeared, and at Kenmare the Old Red Sandstone is followed immediately and conformably by the Limestone with its underlying shale. Mr. Jukes held that the Carboniferous Slate is the equivalent of part of the Devonian rocks of Devon and Cornwall.

The Carboniferous Limestone swells out to a vast thickness, and covers a large part of Ireland. It attains a maximum in the west and south-west, where, according to Mr. Kinahan,[1] it consists in Limerick of the following subdivisions:

		Feet.
Upper (Burren) Limestone	Bedded limestone	240
	Cherty zone	20
Upper (Calp) Limestone	Limestones and shales	1000
	Cherty zone	40
Lower Limestone	*Fenestella* limestone	1900
	Lower cherty zone	20
	Lower shaly limestones	280
Lower Limestone Shale		100
		3600

[1] *Geology of Ireland*, p. 72.

The chert (phtanite) bands which form such marked horizons among these limestones are counterparts of others found abundantly in the Carboniferous Limestone of England and Scotland. They have been recently studied by Messrs. Hull and Hardman, who have found them full of siliceous replacements of calcareous foraminifers, crinoids, &c., and who regard them as due to a chemical alteration on the floor of the Carboniferous sea. Portions of the limestone have a dolomitic character, and sometimes are oolitic. Great sheets of melaphyre, felstone, and tuff, representing volcanic eruptions of contemporaneous date, are interpolated in the Carboniferous Limestone of Limerick and other parts of Ireland. As the limestone is traced northwards it shows a similar change to that which takes place in the north of England, becoming more and more split up with sandstone, shale, and coal-seams, until, at Ballycastle, it presents exactly the characters of the coal-bearing part of the formation in Scotland.[1]

Millstone Grit.—This name is given to a group of sandstones and grits, with shales and clays, which runs persistently through the centre of the Carboniferous system from South Wales into the middle of Scotland. In South Wales it has a depth of 400 to 1000 feet; in the Bristol coal field, of about 1200 feet. Traced northwards it is found to be intercalated with shales, fire-clays, and thin coals, and, like the lower members of the Carboniferous system, to swell out to enormous dimensions in the Pennine region. In North Staffordshire, according to Mr. Hull, it attains a thickness of 4000 feet, which in Lancashire increases to 5500 feet. These massive accumulations of sediment were deposited on the north side of a barrier of more ancient Palæozoic rocks, which, during all the earlier part of the Carboniferous period, seems to have extended across central England, and which was not submerged until part of the Coal-measures had been laid down. North of this great area of deposit the Millstone Grit thins away to not more than 400 or 500 feet. It continues a comparatively insignificant formation in Scotland, attaining its greatest thickness in Lanarkshire and Stirlingshire, where it is known as the Moor Rock. In Ayrshire it does not exist, unless its place be represented by a few beds of sandstone at the base of the Coal-measures.

The Millstone Grit is generally barren of fossils. When they occur they are either plants like those in the coal-bearing strata above and below, or marine organisms of Carboniferous Limestone species. In Northumberland, indeed, it contains a band of limestone undistinguishable from some of those in the Yoredale group and Scaur limestone.

Coal-Measures.—This division of the Carboniferous system consists of numerous alternations of grey, white, yellow, sometimes reddish, sandstone, dark-grey and black shales, clay-ironstones, fire-clays, and coal-seams. In South Wales it attains a maximum depth of about 12,000 feet; in the Bristol coal-field it is 5090 feet. But in these districts, as in the rest of the Carboniferous areas of Britain, we cannot be sure that all the Coal-measures originally deposited now remain, for they are always unconformably covered by later formations. Palæontological considerations, to be immediately adverted to, render it probable that the closing part of the Carboniferous period is not now represented in Britain by fossiliferous strata. Whether or not it ever was so represented cannot be determined, owing to the denudation which occurred before

[1] Hull's *Physical Geology and Geography of Ireland*, p. 30.

the deposition of the overlying Permian rocks. So great indeed was the erosion that the Permian sandstones are sometimes found resting even on the Carboniferous Limestone. In North Staffordshire the depth of Coal-measures is about 5000 feet, which in South Lancashire increases to 8000. These great masses of strata diminish as we trace them eastwards and northwards. In Derbyshire they are about 2500 feet thick, in Northumberland and Durham about 2000 feet, and about the same thickness on the west side of the island in the Whitehaven coal-field. In Scotland they attain a maximum of over 2000 feet.

The Coal-measures are susceptible of local subdivisions indicative of different and variable conditions of deposit. The following tables show the more important of these:

Glamorganshire.	South Lancashire.	Central Scotland.
Feet.	Feet.	Feet.
Upper series: sandstones, shales, &c., with 26 coal-seams, more than . . 3400	Upper series: shales, red sandstones, Spirorbis limestone, ironstone, and thin coal seams . 1600 to 2000	Upper red Sandstones and clays, with Spirorbis limestone, upwards of . 150
Pennant Grit: hard, thick-bedded sandstones, and 15 coal-seams . . . 3246	Middle series: sandstones, shales, clays, and thick coal-seams. The chief repository of coal 3000 to 4000	True coal measures: sandstones, shales, fire-clays, with bands of blackband, ironstone, and numerous seams of coal. Thickness in Lanarkshire upwards of 2000
Lower series: shales, ironstones, and 34 coal-seams . 450 to 850	Lower or Gannister series: flagstones, shales, and thin coals . . 1400 to 2000	
Millstone Grit.	Millstone Grit.	Moor Rock, or Millstone Grit.

The numerous beds of compressed vegetation form the most remarkable feature of the Coal-measures. As already stated each coal seam is usually underlaid by a seam of fire-clay (*mur* of the Belgian coal-fields), which, traversed in all directions by rootlets, and free or nearly free of alkalies and iron, is the soil on which the plants that formed the coal grew. A coal-seam accordingly marks a former surface of terrestrial vegetation, and the fissile micaceous sandstones that overlie it show the nature of the sediment under which it was eventually buried.

The Coal-measures of Britain have not yet been very precisely subdivided into palæontological zones. The lower portions or Gannister beds of Lancashire contain at least 70 species of undoubtedly marine fossils (*Goniatites Listeri*, six species of *Nautilus*, *Aviculopecten papyraceus*, *Lingula squamiformis*, &c.), together with such shells as *Anthracosia*, probably indicating brackish water. The middle and upper divisions are characterized by the prevalence of species of *Anthracosia*, *Anthracoptera*, and *Anthracomya*. Some of the more characteristic fishes are *Strepsodus sauroides* (Fig. 353), *Rhizodopsis sauroides*, *Megalichthys Hibberti*, *Cheirodus granulosus* (Fig. 353), *Janassa linguiformis*, *Ctenacanthus hybodoides* (Fig. 342), *Pleuracanthus lævissimus*, *Ctenoptychius apicalis*. Some species range from bottom to top of the Coal-measures—e.g. *Ctenoptychius pectinatus* and *Gyracanthus tuberculatus*.[1]

On the Continent of Europe the Carboniferous system occupies

[1] My friend Dr. Traquair has been kind enough to furnish me with information on this subject which he has so carefully studied.

many detached areas or basins—the result partly of original deposition, partly of denudation, and partly of the spread and overlap of more recent formations. There can be no doubt that the English Carboniferous Limestone once extended continuously eastward across the north of France, along the base of the Ardennes, through Belgium, and across the present valley of the Rhine into Westphalia. From the western headlands of Ireland this calcareous formation can thus be traced eastward for a distance of 750 English miles into the heart of Europe. It then begins to pass into a series of shales and sandstones, which, as already remarked, represent proximity to shore like the similar strata in the north of England and Scotland. In Silesia, and still much further eastwards in central and southern Russia, representatives of the Carboniferous Limestone appear, but interstratified, as in Scotland, with coal-bearing strata. Traces of the same blending of marine and terrestrial conditions are found also in the north of Spain. But over central France, and eastwards through Bohemia and Moravia into the region of the Carpathians, the Coal-measures rest directly upon older Palæozoic groups, most commonly upon gneiss and other crystalline rocks. These tracts had no doubt remained above water during the time of the Carboniferous Limestone, but were gradually depressed during that of the Coal-measures.

France and Belgium.—In Belgium and the north of France the British type of the Carboniferous system is well developed.[1] It comprises the following subdivisions:

Coal-measures—Système (Étage) Houiller.

- Zone of the gas-coals (*Charbons à gaz*, rich bituminous coals, with 28 to 40 per cent. of volatile matter), containing 47 seams of coal. *Pecopteris nervosa, P. dentata, P. abbreviata, Alethopteris Serlii, Neuropteris heterophylla, Sphenopteris irregularis, S. macilenta, S. coralloides, S. herbacea, S. furcata, Calamites Suckowii, Annularia radiata, Sphenophyllum erosum, Sigillaria tessellata, S. mamillaris, S. rimosa, S. laticosta, Dorycordaites.*
- Zone of the "Charbons gras" (18 to 28 per cent. volatile matter), soft caking coals (21 seams), well suited for making coke. *Sphenopteris nummularia, S. macilenta, S. chærophylloides, S. artemisifolia, S. herbacea, S. irregularis, Neuropteris gigantea, Alethopteris Serlii, A. valida, Calamites Suckowii, Sphenophyllum emarginatum, Sigillaria polyploca, S. rimosa, S. laticosta, Trigonocarpon Nœgerathii.*
- Zone of the "Charbons demi-gras" (12 to 18 per cent. volatile matter), 29 seams of coal, chiefly fitted for smithy and iron-work purposes. *Sphenopteris convexifolia, S. Hœninghausi, S. trichomanoides, S. furcata, S. Schillingsii, S. irregularis, Lonchopteris rugosa, Calamites Suckowii, Annularia radiata, Sigillaria mammilaris, S. elegans, S. piriformis, S. elliptica, S. scutellata, S. Groeseri, S. lævigata, S. rugosa, Halonia tortuosa.*
- Zone of the "Charbons Maigres." Lean or poor coals (20 to 25 seams), only fit for making bricks or burning lime (9 to 12 per cent. volatile matter). *Pecopteris Loshii, P. pennæformis, Neuropteris heterophylla, Alethopteris lonchitica, Sphenophyllum saxifragæfolium, Annularia radiata, Sigillaria conferta, S. Candolli, S. Voltzii, Calamites Suckowii, Lepidodendron rhodeanum, L. pustulatum, Lepidophloios laricinus.*
- Zone of *Productus carbonarius. Goniatites diadema, G. atratus, Spirifera mesogonia, S. glabra, S. trigonalis, Orthis crenistria, Productus semireticulatus, P. marginalis, Avicula papyracea, Schizodus sulcatus.*

Millstone Grit.

- Sandstone or quartzites passing into conglomerates, separated from the Carboniferous limestone below by carbonaceous shales with some thin coal-seams; chiefly developed towards the north-east (Liège, Aix-la-Chapelle.)

[1] Gosselet's *Esquisse*, Mourlon's "Géologie."

Carboniferous Limestone—Calcaire Carbonifère, Système Calcareux.

	Thickness in metres in area of the Sambre.	Thickness in metres in area of the Meuse.	Subdivision of M. Dupont.
Limestone of Visé. Often poor in fossils, but distinguished by *Productus giganteus*.	50	250	Assise VI.
Limestone of Limont (Napoleon marble of Boulonnais). Fossils numerous, *Productus undatus*, *P. semireticulatus*, *Spirifera glabra*, *S. duplicicosta*, *Rhynchonella pleurodon*, *Terebratula sacculus*	10		
Limestone of Haut Banc, compact or oolitic in south part of Sambre basin, with *Productus sublævis*; but in north part of that basin, as well as on the Meuse and in the Boulonnais, *Productus cora* replaces *P. sublævis*	40	150	Assise V.
Dolomite of Namur, well developed between Namur and Liège, and extending into the Boulonnais (Hure dolomite), alternating with grey limestone, containing *Chonetes comoïdes*	40		
Limestone of Bachant, grey, bluish-black, or black, with cherts (phtanites). *Productus cora* (and sometimes *P. giganteus*), *Spirifera tricornis*, *Dentalium priscum*, *Euomphalus cirroides*, *Nautilus sulcatus*, *Orthoceras munsterianum*	35	100	Assise IV.
Limestone of Waulsort, grey, often dolomitic; only seen in area of the Meuse. *Spirifera cuspidata*, *Conocardium aliforme* . . .	0	100	Assise III.
Limestone of Anseremme, grey and blue-veined limestone and dolomite. *Productus semireticulatus*, *Spirifera mosquensis*, *S. cuspidata*, *Orthis resupinata*	8	60	Assise II.
Limestone of Dinant, only found in the Meuse area. *Productus semireticulatus*, *P. Flemingii*, *Pecten intermedius* . . .	0	100	Assise I.
Limestone of Ecaussines ("petit granite"), crinoidal limestone. *Phillipsia gemmulifera*, *Productus semireticulatus*, *Spirifera mosquensis*, *Orthis crenistria*, *O. Michelini*, *Leptæna rhomboidalis*	25		
Limestones and shales of Avesnelles, black limestone (16 metres), resting upon argillaceous shales (40 metres). Among the numerous fossils of the limestone are *Productus Flemingii*, *P. Heberti*, *Chonetes variolaris*, *Rhynchonella pleurodon*, *Spirifera mosquensis*, *Euomphalus equalis*, *Pecten Sowerbyi*	50		
	258	760 metres.	

The base of these strata passes down conformably into the Devonian system, with which, alike by palæontological and petrographical characters, it is closely linked. The Carboniferous rocks of the north of France and of Belgium have undergone considerable disturbance. A remarkable fault ("la grande faille" of this region) resulting from the rupture of an isoclinal syncline, and the consequent sliding of the inverted side over higher beds, runs from near Liège westwards into the Boulonnais, with a general but variable hade towards the south. On its

outhern side lie the lower Devonian beds, below which the Carboniferous Limestone, and even Coal-measures are made to plunge. Bores and pits near Liège at the one end, and in the Boulonnais at the other, have reached workable coal, after piercing the inverted Devonian rocks. By continuing the boring the same coals are found at lower levels in their normal positions. Besides this dominant dislocation many minor faults and plications have taken place in the Carboniferous area, some of the coal-seams being folded zig-zag, so that at Mons a bed may be perforated six times in succession by the same vertical shaft, in a depth of 350 yards. At Charleroi a series of strata, which in their original horizontal position occupied a breadth of 8½ miles, have been compressed into rather less than half that space by being plicated into twenty-two zig-zag folds.

Southwards the area of crystalline rocks in Central France is dotted with numerous small Carboniferous basins which contain only portions of the Coal-measures. It would appear, however, that some of the surrounding schists are really altered representatives of the lower parts of this system, for undoubted Carboniferous limestone fossils have been found in them between Roanne and Lyons, and near Vichy. Even as far south as Montpellier, beds of limestone full of *Productus giganteus* and other characteristic fossils are covered by a series of workable coals. The Carboniferous limestone is well developed westward in the Cantabrian mountains in the north of Spain, where it likewise is surmounted by coal-bearing strata. Grand'Eury, from a consideration of the fossils, regards the coal-basins of the Roannais, and lower part of the basin of the Loire, as belonging to the age of the "culm and upper greywacke," or of strata immediately underlying the true Coal-measures. But the numerous isolated coal basins of the centre and south of France he refers to a much later age. He regards these as containing the most complete development of the upper coal, properly so called, enclosing a remarkably rich, and still little known, flora, which serves to fill up the palæontological gap between the Carboniferous and Permian periods.[1] Some of these small isolated coal basins are remarkable for the extraordinary thickness of their coal-seams. In the most important of their number, that of St. Etienne, from 15 to 18 beds of coal occur, with a united thickness of 112 feet, in a total depth of 2500 feet of strata. In this basin near Chalons and Autun the main coal averages 40, but occasionally swells out to 130 feet, and the Coal-measures are covered, apparently conformably, by the Permian rocks, from which so remarkable a series of saurian remains has recently been obtained.

Germany.[2]—Tracing the extension of the Carboniferous system, we find the upper, or Coal-measures, portion extending in detached basins north-eastwards from Central France into Germany. One of the most important of these, the basin of Pfalz-Saarbrücken, lying unconformably on Devonian rocks, contains a mass of Coal-measures believed to reach a maximum thickness of not less than 20,000 feet, and divided into two groups:

2. Upper or Ottweiler beds, from 6500 to 11,700 feet thick, consisting of red sandstones at the top, and of sandstones and shales, containing 20 feet of coal in various seams. *Pecopteris arborescens, Odontopteris obtusa, Anthracosia, Estheria, Leaia;* fish remains.

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[1] Grand'Eury, "Flore Carbonifère."

[2] Geinitz, "Die Steinkohlen Deutschlands," Munich, 1865.

1. Lower or main coal-bearing (Saarbrücken) beds, 5200 to 9000 feet thick, with 82 workable and 142 unworkable coal-seams, or in all between 350 and 400 feet of coal. Abundant plants of the middle and lower zone of the upper coal flora.

Among the small coal-fields of Germany are those of Ibbenbüren and Presberg, Halle, Harz, and Thüringer Wald. That of Zwickau, in Saxony, contains about 1700 feet of strata with 12 chief seams of coal, one of which (Russkohle) is sometimes 25 feet thick. Geinitz, adopting the order of succession of the fossil plants as his guide, has proposed to subdivide the Saxon Coal-measures as follows in descending order:

3. The Fern zone, marked by the profusion of its ferns (*Sphenopteris*, *Hymenophyllites*, *Schizopteris*, *Odontopteris*, *Neuropteris*, *Cyclopteris*, *Alethopteris*, *Caulopteris*). This is underlaid by
2. The Sigillaria Zone, containing many species of *Sigillaria*, also *Lepidodendron*, *Calamites*, *Asterophyllites*, and a few ferns.
1. The Lycopod Zone, abounding in *Sagenaria* (*Lepidodendron*) *veltheimiana*, with *Sphenopteris distans*, *Calamites transitionis*, &c. This zone is compared by Geinitz with the Culm. According to Grand'Eury the Saxon Coal-measures belong to the upper group of the middle coals and lower group of the upper coals.

Eastern Europe.—In Moravia, Silesia, Poland, and Russia, the Carboniferous Limestone reappears as the base of the Carboniferous system, but not in the massive calcareous development which it presents in Belgium and England. One of its most characteristic phases is that to which the name "Culm" (applied originally to the inferior slaty coal of Devonshire) has been given, when it becomes a series of shales, sandstones, greywackes, and conglomerates, in which the abundant fauna of the limestone is reduced to a few molluscs (*Productus antiquus*, *P. latissimus*, *P. semireticulatus*, *Posidonomya Becheri*, *Goniatites sphæricus*, *Orthoceras striatulum*, &c.). The *Posidonomya* particularly characterizes certain dark shales known as Posidonia schists. About 50 species of plants have been obtained from the Culm, typical species being *Calamites transitionis*, *Lepidodendron veltheimianum*, *Stigmaria ficoides*, *Sphenopteris distans*, *Cyclopteris tenuifolia*. This flora bears a strong resemblance to that of the Calciferous Sandstones of Scotland.

The coal-field of Pilsen in Bohemia occupies about 300 square miles. It consists mainly of sandstone, passing sometimes into conglomerate, and interstratified with shales and a few seams of coal which do not exceed a total thickness of 20 feet of coal. In its upper part is an important seam of shaly gas-coal (Plattel, or Brettelkohle), which, besides being valuable for economic purposes, has a high palæontological interest from Dr. Fritsch's discovery in it of a rich fauna of saurians and fishes. The plants above and below this seam are ordinary typical Coal-measure forms, but these animal remains present such close affinities to Permian forms, that the strata containing them may belong to the Permian system (see p. 754). What are believed to be true Permian rocks in the Pilsen district seem to overlie the coals unconformably.

In Russia the Scottish type of the Carboniferous system reappears. In the central provinces the coal-field of Tula, said to occupy an area of 13,000 square miles, lies conformably on the Old Red Sandstone, and

contains limestones, full of Carboniferous Limestone fossils and a few poor seams of coal. In the south of the empire the coal-field of the Donetz, covering an area of 11,000 square miles, contains 60 seams of coal, of which 44, having a united thickness of 114 feet, are workable. Again, on the flanks of the Ural Mountains, the Carboniferous Limestone series has been upturned and contains some workable coal-seams. It would appear, therefore, that this particular type of mingled marine and terrestrial strata of Carboniferous age, occupies a vast expanse under later formations in the east of Europe.

Asia, Australia.—The Carboniferous system is extensively developed in Asia. Over the great plain of China, an area of Coal-measures 30,000 square miles in extent lies quite flat upon a mass of limestone forming an escarpment 2000 to 3000 feet high, and the coal-seams (30 feet thick) are said to be horizontal for 200 miles. In Australia, important tracts of true Carboniferous rocks with coal-seams range down the eastern colonies and are specially developed in New South Wales, where the coals are numerous, and from 3 to 30 feet thick. Among the plants of these strata are some well-known European forms, as *Alethopteris lonchitica*, *Bornia radiata*, *Calamites varians*, *Glossopteris browniana*, *Lepidodendron nothum*, *L. rimosum*, and *L. veltheimianum*. The fauna includes the wide-spread and characteristic Carboniferous Limestone forms *Lithostrotion basaltiforme*, *L. irregulare*, *Fenestella plebeia*, *Athyris Royssii*, *Orthis Michelini*, *O. resupinata*, *Productus aculeatus*, *P. cora*, *P. longispinus*, *P. punctatus*, *P. semireticulatus*, and many more.[1]

North America.—Rocks corresponding in geological position and the general aspect of their organic contents with the Carboniferous system of Europe are said to cover an area of more than 200,000 square miles in the United States and British North America. The following table shows the subdivisions which have been established among them:

Carboniferous.	Coal-measures,—a series of sandstones, shales, ironstones, coals, &c., varying from 100 feet in the interior continental area to 4000 feet in Pennsylvania, and more than 8000 feet in Nova Scotia. The plant remains include forms of *Lepidodendron*, *Sigillaria*, *Stigmaria*, *Calamites*, ferns, and coniferous leaves and fruits. The animal forms embrace in the marine bands species of *Spirifera*, *Productus*, *Bellerophon*, *Nautilus*, &c. Among the shales and carbonaceous beds numerous traces of insect life have been obtained, comprising species related to the may-fly and cockroach. Spiders, scorpions, centipedes, limuloid crabs, and land snails like the modern *Pupa* have also been met with. The fish remains comprise teeth and ichthyodorulites of placoid genera, and a number of ganoids (*Eurylepis*, *Cœlacanthus*, *Megalichthys*, *Rhizodus*, &c.). Several labyrinthodonts occur, and true reptiles are represented by one saurian genus found in Nova Scotia, the *Eosaurus*. In the western Territories the Upper Carboniferous rocks consist of a massive group of limestone 2000 feet thick, resting on Lower Carboniferous ("Weber Quartzite" of King) estimated at 6000 to 10,000 feet, but with no coals. Millstone Grit,—a group of arenaceous and sometimes conglomeratic strata, with occasional coal-seams, only 25 feet thick in some parts of New York, but swelling out to 1500 feet in Pennsylvania.

[1] Richthofen's "China," vol. ii. W. B. Clarke, "Fossiliferous Formations of N. S. Wales," 1875. R. Etheridge, Jun., "Catalogue of Australian Fossils," 1878.

Sub-Carboniferous.

In the Mississippi basin where the sub-Carboniferous groups are best developed, they present the following subdivisions in descending order:

Chester group.—Limestones, shales, and sandstones, sometimes 600 feet.

St. Louis group.—Limestones with shale, in places 250 feet.

Keokuk group.—Limestone with chert layers and nodules.

Burlington group.—Limestone, in places with chert and hornstone, 25 to 200 feet.

Kinderhook group.—Sandstones, shales, and thin limestones, 100 to 200 feet, resting on the Devonian black shale.

The sub-Carboniferous groups are mainly limestones, but contain here and there remains of the characteristic Carboniferous land vegetation. Crinoids of many forms abound in the limestones. A remarkable polyzoon, *Archimedes*, occurs in some of the bands. The brachiopods are chiefly represented by species of *Spirifera* and *Productus*; the lamellibranchs by *Myalina*, *Schizodus*, *Aviculopecten*, *Nucula*, *Pinna*, and others; the cephalopods by *Orthoceras*, *Nautilus*, *Goniatites*, *Gyroceras*, &c. The European genus of trilobite, *Phillipsia*, occurs. Numerous teeth and fin-spines of selachian fishes give a further point of resemblance to the European Carboniferous Limestone. Some of the rippled rain-pitted beds contain amphibian foot-prints—the earliest American forms yet known.

Section V.—Permian or Dyas.

§ 1. General Characters.

The Carboniferous rocks are overlaid, sometimes conformably, but in Europe for the most part unconformably, by a series of red sandstones, conglomerates, breccias, marls, and limestones. These used to be reckoned as the highest part of the Coal formation. In England they received the name of the "*New* Red Sandstone" in contradistinction to the "*Old* Red Sandstone" lying beneath the Carboniferous rocks. The term "Poikilitic" was formerly proposed for them, on account of their characteristic mottled appearance. From their wide development in the Russian province of Perm they were styled "Permian" by Murchison, De Verneuil, and Keyserling. In Germany, where they exhibit a well-marked grouping into two great series of deposits, they have received the name of "Dyas." In North America, where no good line of subdivision can be made at the top of the Carboniferous system, the term "Permo-Carboniferous" has been adopted to denote the transitional beds at the top of the Palæozoic series.

In Europe two distinct types of the system can be made out. In one of these (Dyas) the rocks consist of two great divisions: (1) a lower series of red sandstones and conglomerates, and (2) an upper group of limestones and dolomites. In the other (Russian or Permian) the strata are of similar character but are interstratified in such a way as to present no twofold petrographical subdivision.

Rocks.—The prevailing materials of the Permian series in Europe are undoubtedly red sandstones, passing now into conglomerates and now into fine shales or marls. In their coarsest forms these detrital deposits consist of conglomerates and breccias composed of fragments of different crystalline or older Palæozoic rocks (granite, diorite, gneiss, mica-schist, quartzite, greywacke, sandstone, &c.), that

vary in size up to blocks a foot or more in diameter. Sometimes, these stones are well rounded, but in many places they are only partially so, while here and there they are quite angular and then constitute breccias. The pebbles are held together by a brick-red ferruginous, siliceous, sandy, or argillaceous cement. The sandstones are likewise characteristically brick-red in colour, generally with green or white layers and spots of decoloration. The marls show still deeper shades of red, passing occasionally into a kind of livid purple; they are crumbling sandy clay-rocks, sometimes merging into more or less fissile shales. Of the argillaceous beds of the system the most remarkable are those of the marl-slate or Kupferschiefer—a brown or black often distinctly bituminous shale or marl, which in certain parts of Germany is charged with ores of copper. The limestone, so characteristic a feature in the "Dyas" development of the system, is a compact, well-bedded, somewhat earthy, and usually more or less dolomitic rock. It is the chief repository of the Permian invertebrates. With it are associated bands of dolomite, either crystalline and cavernous (Rauchwacke) or finely granular and crumbling (Asche); also bands of gypsum, anhydrite, and rock-salt. In certain localities (the Harz, Bohemia, Autun) seams of coal are intercalated among the rocks, and with these, as in the Coal-measures, are associated bituminous shales and nodular clay-ironstones. In Germany and in the south-west of Scotland the older part of the Permian system contains abundant contemporaneous masses of eruptive rock, among which occur porphyrite, melaphyre, and various forms of quartz-porphyry.

Some of the breccias in the west of England contain striated stones, which, according to Sir A. C. Ramsay, indicate the existence of glaciers in Wales during the Permian period.

The Permian system in Europe, from the prevalent red colour of its rocks, the association of dolomite, rock-salt, saliferous clays, gypsum, and anhydrite, has evidently been deposited in isolated basins in which the water, cut off more or less completely from the sea, underwent concentration until chemical precipitation could take place. Looking back at the history of the Carboniferous rocks we can understand how such a change in physical geography was brought about. The Carboniferous Limestone sea having been excluded from the region, wide lagoons occupied its site, and these, as the land slowly went down, crept over the old ridges that had for so many ages been prominent features. The downward subterranean movement was eventually varied by local elevations, and at last the Permian basins came to be formed. As a result of these disturbances the Permian rocks overlap the Carboniferous, and even cover them in complete discordance.[1]

Life.—The conditions under which the European Permian rocks were deposited must have been eminently unfavourable to life.

[1] The discordance, however, sometimes disappears, and then the Carboniferous and Permian rocks shade into each other.

Accordingly we find that the rocks are on the whole singularly barren of organic remains. From the rich faunas of the Silurian, Devonian, and Carboniferous systems we enter the Permian formation and find only somewhere about 300 species of organisms.

The Permian flora presents many points of resemblance to the Carboniferous.[1] According to Grand'Eury upwards of 50 species of plants are common to the two floras. Among the forms which rise into the Permian rocks and disappear there are *Calamites Suckowii, C. approximatus, Asterophyllites equisetiformis. A. rigidus, Pecopteris elegans, Odontopteris Schlotheimii, Sigillaria Brardii* (and others), *Stigmaria ficoides, Cordaites borassifolius,* &c. Others which are mainly Permian are yet found in the highest coal-beds of France, *e.g. Calamites gigas, Calamodendron striatum, Arthropitus ezonata, Tæniopteris abnormis, Walchia pinniformis,* &c. But the Permian flora has some

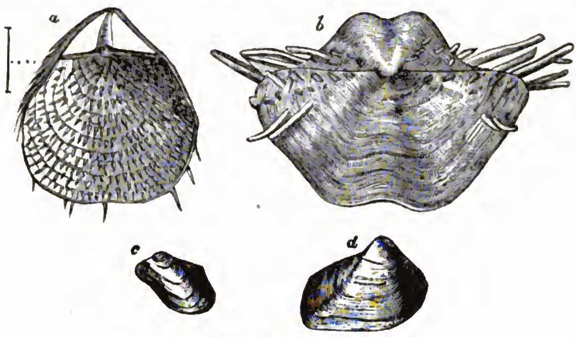

Fig. 355.—Permian Molluscs.
a, Strophalosia Goldfussi (Munst.) (enlarged); *b*, Productus horridus (Sow.); *c*, Bakevellia tumida (King); *d*, Schizodus Schlotheimii (Geinitz).

distinctive characters; as the variety and quantity of the ferns united under the genus *Callipteris,* which do not occur in the Coal-measures, the profusion of tree-ferns (*Psaronius,* of which 24 species are described by Göppert, *Protopteris, Caulopteris,* &c.) and of *Equisetites,* and the abundance of *Walchia pinniformis* and *W. filiciformis.* The most characteristic plants throughout the German Permian groups are *Odontopteris obtusiloba, Callipteris conferta, Walchia pinniformis,* and *Calamites gigas.* The last representatives of the ancient tribes of the lepidodendra, sigillarioids, and calamaries appear in the Permian system.

The impoverished fauna of the Permian rocks is found almost wholly in the limestones and brown shales, the red conglomerates and sandstones being, as a rule, devoid of organic contents. A few

[1] See Göppert's "Die Fossile Flora der Permischen Formation," Cassel, 1864–5.

corals (*Stenopora*) and polyzoa (*Fenestella, Synocladia, Acanthocladia*) occur in the limestones; the echinoderms are few, the chief crinoids being species of *Cyathocrinus*. Among the brachiopods the most conspicuous are species of *Productus, Camarophoria, Spirifera*, and *Strophalosia* (Fig. 355). Lamellibranchs are more numerous, characteristic genera being *Allorisma, Solemya, Schizodus, Edmondia, Arca, Avicula, Bakevellia* (Fig. 355), *Pecten*. Among the few gasteropods, forms of *Chemnitzia, Turbo, Murchisonia, Pleurotomaria*, and *Chiton* have been recorded. An occasional *Nautilus* or *Orthoceras* represents the rich cephalopodan fauna of the Carboniferous

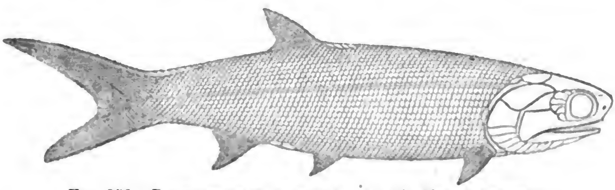

FIG. 356.—PALÆONISCUS MACROPOMUS. AG. (½) KUPFERSCHIEFER. From a restoration by Dr. Traquair.

Limestone. Fishes are proportionately better represented in the Permian rocks than the invertebrates. They chiefly occur in the marl-slate or Kupferschiefer. The most common genera are *Palæoniscus* (Fig. 356), which is specially characteristic, *Platysomus* (Fig. 357), and *Pygopterus*.

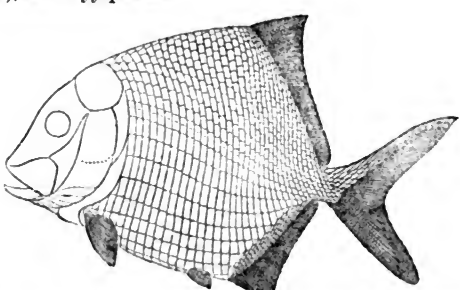

FIG. 357.—PLATYSOMUS STRIATUS. AG. (½) MAGNESIAN LIMESTONE. Restored by Dr. Traquair.

Amphibian life appears to have been abundant in Permian times, for some of the sandstones of the system are covered with footprints, assigned to the extinct order of Labyrinthodonts. Occasional skulls and other bones have been met with referable to *Lepidotosaurus*,

Zygosaurus, &c. The remains of comparatively few forms, however, had been found until the remarkable discoveries of Dr. Anton Fritsch in the basins of Pilsen and Rakowitz in Bohemia. The strata of these localities have been already (p. 748) referred to as containing an abundant and characteristic coal-flora, yet with a fauna that is as decidedly like that of known Permian rocks. According, therefore, as we give preference to the plants or the animals, the strata may be ranked as Carboniferous or as Permian. They have yielded no fewer than forty-three species of amphibians, of which Dr. Fritsch is publishing elaborate descriptions. Those described up to this time are *Branchiosaurus* (a form resembling an earth-salamander in possessing gills, and of which the largest specimen is only about 2½ inches long), *Sparodus, Hylonomus, Dawsonia, Melanerpeton, Dolichosoma, Ophiderpeton*, and *Palæosiren*.[1] From the corresponding strata of Autun in Central France, M. Gaudry has described some additional forms *Actinodon, Protriton*, a new batrachian genus *Pleuroneura*, and *Euchirosaurus*, a larger and more highly organized form than any yet known from the Palæozoic rocks of France.[2] The Kupferschiefer of Germany and the corresponding beds in England have yielded the earliest known European lacertilian reptile—the *Proterosaurus*, one distinguishing feature in which is the crocodilian character of having the teeth planted in distinct sockets.

§ 2. Local Development.

Britain.[3]—In England on a small scale, a representative is to be found of the two contrasted types of the European Permian system. On the east side of the island from the coast of Northumberland southwards to the plains of the Trent, a true "Dyas" development is exhibited, the Magnesian limestone and Marl-slate forming the main feature of the system; on the west side of the Pennine chain, however, the true Permian or Russian facies is presented. Arranged in tabular form the rocks of the two areas may be grouped as follows:

	W. of England. (Permian or Russian type.)	E. of England.[1] (Dyas or German type.)
Red sandstones, clays, and gypsum .	600 ft.	50–100 ft.
Magnesian limestone . . . . Marl slate	10–30 „	600 „
Lower red and variegated sandstone, reddish brown and purple sandstones and marls, with calcareous conglomerates and breccias . .	3000 „	100–250 „

[1] A. Fritsch, "Fauna der Gaskohle und der Kalksteine der Permformation Böhmens," Prag, 1881–2.

[2] Gaudry, *Bull. Soc. Géol. France*, vii. (3 sér.), p. 62.

[3] Sedgwick, *Trans. Geol. Soc.* iii. (1835), p. 37; iv. 383; Murchison, "Siluria," p. 308; Hull, "Triassic and Permian Rocks of Midland Counties of England" in *Mem. Geol. Surv.* 1869; *Q. J. Geol. Soc.* xxv. 171; xxix. p. 402; Ramsay, *Op. cit.* xxvii. p. 241; E. Wilson, *Op. cit.* xxxii. p. 533; D. C. Davies, *Op. cit.* xxxiii. p. 10; H. B. Woodward, *Geol. Mag.* 1874, p. 385; T. V. Holmes, *Q. J. Geol. Soc.* xxxvii. p. 286.

Lower Sandstone.—This subdivision attains its greatest development in the vale of the Eden, where it consists of brick-red sandstones, with some beds of calcareous conglomerate or breccia, locally known as "brockram," derived from the waste of the Carboniferous Limestone. These red rocks, extending across the Solway into the valleys of the Nith and Annan in the south of Scotland, lie unconformably on the Lower Silurian rocks, from which their breccias have been derived, but near Dumfries some calcareous breccias or "brockrams" occur. These brecciated masses have evidently accumulated in small lakes or narrow fjords. In the basin of the Nith, and also in Ayrshire, numerous small volcanic vents and sheets of porphyrite and tuff are associated with the red sandstones, marking a volcanic district of Permian age. The vents rise through Coal-measures as well as more ancient rocks. Much further south, in Staffordshire, and in the districts of the Clent and Abberley Hills, the brecciated conglomerates in the Permian series attain a thickness of 400 feet. They have been shown by Ramsay to consist in large measure of volcanic rocks, grits, slates, and limestones, which can be identified with rocks on the borders of Wales. Some of their blocks are three feet in diameter and show distinct striation. These Permian drift-beds, according to Ramsay, cannot be distinguished by any essential character from modern glacial drifts, and he has no doubt that they were ice-borne, and, consequently, that there was a glacial period during the accumulation of the Lower Permian deposits of the centre of England.

Like red rocks in general the Lower Permian beds are almost barren of organic remains. Such as occur are indicative chiefly of terrestrial surfaces. Plant remains occasionally appear, such as *Caulerpites* (supposed to be of marine growth), *Lepidodendron dilatatum*, *Calamites*, *Sternbergia*, and fragments of coniferous wood. The cranium of a labyrinthodont (*Dasyceps*) has been obtained from the Lower Permian rocks at Kenilworth. Footprints referred to members of the same extinct order have been observed abundantly on the surfaces of the sandstones of Dumfriesshire, and also in the vale of the Eden.

Magnesian Limestone group.—This subdivision is the chief repository of fossils in the Permian system. Its strata are not red, but consist of a lower zone of hard brown shale with occasional thin limestone bands (Marl Slate) and an upper thick mass of dolomite (Magnesian Limestone). The latter is the chief feature in the Permian (Dyas) development of the east of England. Corresponding with the Zechstein of Germany, as the Marl Slate does with the Kupferschiefer, it is a very variable rock in lithological characters, being sometimes dull, earthy, fine-grained, and fossiliferous, in other places quite crystalline, and composed of globular, reniform, botryoidal, or irregular concretions of crystalline and frequently internally radiated dolomite. The Magnesian Limestone runs as a thick persistent zone down the east of England. It is represented on the Lancashire and Cheshire side by bright red and variegated sandstone covered by a thin group of red marls, with numerous thin courses of limestone, containing *Schizodus*, *Bakevellia*, and other characteristic fossils of the Magnesian Limestone.

The Magnesian Limestone group has yielded about 100 species belonging to 46 genera of fossils—a singularly poor fauna when contrasted with that of the Carboniferous system below. The brachiopods (9 genera, 21

species) include *Productus horridus*, *Camarophoria multiplicata*, *C. Schlotheimi*, *Strophalosia Goldfussi*, *Lingula Credneri*, and *Terebratula elongata*. The lamellibranchs number 16 genera and 31 species, among which *Schizodus Schlotheimi*, *Bakevellia tumida*, *B. antiqua*, *B. ceratophaga*, *Mytilus squamosus*, and *Arca striata* are characteristic. The univalves are represented by 11 genera and 26 species, including *Pleurotomaria* and *Turbo* as common genera. Fishes have been obtained chiefly in the Marl Slate, to the number of 21 species belonging to 8 genera, of which *Palæoniscus* is the chief. These small ganoids are closely related to some which haunted the lagoons of the Carboniferous period. Some reptilian remains have been obtained from the group, particularly *Proterosaurus Speneri*, *P. Huxleyi*, and *Lepidotosaurus Duffii*.

Murchison and Harkness have classed as Upper Permian certain red sandstones with thin partings of red shale, and an underlying band of red and green marls and gypsum. These rocks, seen at St. Bees, near Whitehaven, resting on a magnesian limestone, have not yet yielded any fossils.

Germany, &c.—The "Dyas" type of the system attains a great development along the flank of the Harz Mountains, also in Thuringia, Saxony, Bavaria, and Bohemia. On the south side of the Harz it is grouped into the following subdivisions:

Zechstein Group.	Anhydrite, gypsum, rock-salt, marl, dolomite, fetid shale, and limestone. The amorphous gypsum is the chief member of this group; the limestone is sometimes full of bitumen.
	Crystalline granular (*Rauchwacke*) and fine sandy (*Asche*) dolomite (6 to 65 feet).
	Zechstein, an argillaceous thin-bedded compact limestone 15 to 30 (sometimes even 90) feet thick.
	Kupferschiefer—a black bituminous shale not more than about 2 feet thick.
	Zechstein-conglomerate, and calcareous sandstone.
Rothliegende Group.	Upper.—Conglomerates (quartz-porphyry conglomerate) and sandstone, with associated melaphyres and tuffs.
	Middle.—Red clays, shales, and fine shaly sandstones, with bands of quartz-conglomerate and earthy limestone. Melaphyre and porphyrite masses intercalated.
	Lower.—Shaly sandstones, shales (with bituminous bands), and conglomerates.

The name "Rothliegende" or "Rothtodtliegende" (red-layer or red-dead-layer) was given by the miners because their ores disappeared in the red rocks below the copper-bearing Kupferschiefer. The coarse conglomerates have been referred by Ramsay to a glacial origin, like those of the Abberley Hills. They attain the enormous thickness of 6000 feet or more in Bavaria. One of the most interesting features of the formation is the evidence of the contemporaneous outpouring of great sheets of quartz-porphyry, granite-porphyry, porphyrite, and melaphyre, with abundant interstratifications of various tuffs, not unfrequently enclosing organic remains. From the very nature of its component materials, the Rothliegende is comparatively barren of fossils; a few ferns, calamites, and remains of coniferous trees are found in it, particularly towards the base, where indeed they form, in the Mansfeld district, a coal-seam about 5 feet thick.

The plants, all of terrestrial growth, on the whole resemble generically the Carboniferous flora, but seem to be nearly all specifically distinct. They include forms of *Calamites* (*C. gigas*), *Asterophyllites*, and ferns of the genera *Sphenopteris*, *Alethopteris*, *Neuropteris*, *Odontopteris*, with well-

preserved silicified stems of tree-ferns (*Psaronius*, *Tubicaulis*). The conifer *Walchia* (*W. piniformis*) is specially characteristic. Fish remains occur sparingly (*Amblypterus*, *Palæoniscus*, *Acanthodes*), and traces of labyrinthodonts (*Archegosaurus Decheni*) have been met with.

The Zechstein group is characterized by a suite of fossils like those of the Magnesian Limestone group of England. The Kupferschiefer contains numerous fish (*Palæoniscus Freislebeni*, *Platysomus gibbosus*, &c.) and remains of plants (coniferous leaves and fruits and sea-weeds). This deposit is believed to have been laid down in some enclosed sea-basin, the waters of which, probably from the rise of mineral springs connected with some of the volcanic foci of the time, were so charged with metallic salts in solution as to become unfit for the continued existence of animal life. The dead fish, plants, &c., by their decay, gave rise to reduction and precipitation of these salts as sulphides, which thereupon enclosed and replaced the organic forms, and permeated the mud at the bottom. This old sea-floor is now the widely extended band of copper-slate which has so long and so extensively been worked along the flanks of the Harz. After the formation of the Kupferschiefer the area must have been once more covered by clearer water, for the Zechstein contains a number of organisms, among which *Productus horridus*, *Spirifera undulata*, *Strophalosia Goldfussi*, *Schizodus obscurus*, and *Fenestella retiformis* are common. Renewed unfavourable conditions are indicated by the dolomite, gypsum, and rock-salt which succeed. Reasoning upon similar phenomena as developed in England, Ramsay has connected them with the abundant labyrinthodont footprints and other evidences of shores and land, as well as the small number and dwarfed forms of the shells in the Magnesian Limestone, and has speculated on the occurrence of a long "continental period" in Europe, during one epoch of which a number of salt inland seas existed wherein the Permian rocks were accumulated. He compares these deposits to what may be supposed to be forming now in parts of the Caspian Sea.

In Bohemia (pp. 748, 754) and Moravia, where the Permian system is extensively developed, it has been divided into three groups. (1) A lower set of conglomerates, sandstones, and shales, sometimes bituminous. These strata contain diffused copper ores and abound here and there in remains of land-plants and fishes. (2) A middle group of felspathic sandstones, conglomerates, and micaceous shales, with vast numbers of silicified tree-stems (*Araucarites*, *Psaronius*). (3) An upper group of red clays and sandstones, with bituminous shales. Eruptive rocks (melaphyre, porphyrite, &c.) are associated with the whole formation. A zone of red sandstones and conglomerates found on both sides of the Alps below recognized Triassic beds is referred to the Permian system. In the southern Tyrol it includes the well-known mass of red porphyry of Botzen with its associated breccias, tuffs, and red-sandstones.

Russia.[1]—The second or "Permian" type attains an enormous development in Eastern Europe. Its nearly horizontal strata cover by far the largest part of European Russia. They consist of sandstones, marls, shales, conglomerates, limestones (often highly dolomitic), gypsum, rock-salt, and thin seams of coal. In the lower and more sandy half of this series of strata remains of land-plants (*Calamites gigas*, *Cyclopteris*, *Pecopteris*, &c.),

[1] See "Russia and Ural Mountains," Murchison, De Verneuil, and Keyserling: 4to, 2 vols., 1845.

fishes (*Palæoniscus*), and labyrinthodonts occur, but some interstratified bands yield *Productus Cancrini* and other marine shells. The rocks are over wide regions impregnated with copper ores. The upper half of the series consists of clays, marls, limestones, gypsum, and rock-salt, with numerous marine mollusca like those of the Zechstein (*Productus Cancrini*, *P. horridus*, *Camarophoria Schlotheimi*), but with intercalated bands containing land-plants. It would therefore appear that terrestrial and marine conditions must have frequently alternated in Eastern Europe during the deposition of the Permian system of that region.

France.—On the east of France, and stretching intermittently northwards along the flanks of the Vosges, and eastwards into the Black Forest, the Permian system is represented by two massive formations, a lower group of red sandstones, clays, and conglomerates 400 to 500 feet thick, equivalent to the Rothliegende, and an upper group composed of pebbly felspathic sandstone (Grès des Vosges) with vegetable impressions. As already stated, it is probable that the strata overlying the highest coal-measures in some of the numerous basins scattered over the central tracts of France should be referred to the Permian system. The most remarkable of these tracts yet explored is that of Autun, in which a mass of sandstones, conglomerates, and shale, often abundantly bituminous, occurs of unknown, but of great thickness, for a portion of it was bored through to a depth of 410 metres (1345 feet). It contains a bed of magnesian limestone two feet thick. It is specially characterized by its fishes and the remarkable series of reptilian remains described by M. Gaudry.[1]

North America.—The Permian system is hardly represented at all in this part of the globe. In Kansas certain red and green clays, sandstones, limestones, conglomerates, and beds of gypsum lie conformably on the Carboniferous system, and contain a few genera and species of mollusca (*Bakevellia*, *Myalina*, &c.) which occur in the European Permian rocks. It has recently been urged, however, that the upper part of the Appalachian coal-field should be regarded as belonging to the Permian system. These strata, termed the "Upper Barren Measures," are upwards of 1000 feet thick. At their base lies a massive conglomeratic sandstone, above which come sandstones, shales, and limestones, with thin coals, the whole becoming very red towards the top. Professors W. M. Fontaine and J. C. White have shown that out of 107 plants examined by them from these strata 22 are common to the true Pennsylvanian Coal-measures and 28 to the Permian rocks of Europe; that even where the species are distinct they are closely allied to known Permian forms; that the ordinary Coal-measure flora is but poorly represented in the "Barren Measures," while on the other hand vegetable types appear of a distinctly later time, forms of *Pecopteris*, *Callipteridium*, and *Saportæa* foreshadowing characteristic plants of the Jurassic period. These authors likewise point to the indications furnished by the strata themselves of important changes in the physical condition of the American area, and to the remarkable paucity of animal life in these beds as in the red Permian rocks of Europe. The evidence at present before us seems certainly in favour of regarding the upper part of the Appalachian coal-fields as representing the reptiliferous beds overlying the Coal-measures at Autun and their equivalents.[2]

[1] Delafond, *Bull. Soc. Géol. France*, iv. (3e sér.), p. 727. Gaudry, *Op. cit.* vii. (3e sér.), p. 62.

[2] "On the Permian or Upper Carboniferous Flora of W. Virginia and S. W. Pennsylvania," *Second Geol. Surv. Penn. Report*, P.P. 1880.

PART III. MESOZOIC OR SECONDARY.

Section I. Triassic and Rhætic.

It has been already mentioned that the great mass of red rocks, which in England overlie the Carboniferous system, were formerly classed together as New Red Sandstone, but are now ranged in two systems. We have considered the lower of these under the name of Permian. The general facies of organic remains in that division is still decidedly Palæozoic. Its brachiopods and its plants connect it with the Carboniferous rocks below. Hence it is placed at the close of the long series of Palæozoic formations. When, however, we enter the upper division of the red rocks, though the general lithological characters remain very much as in the lower group, the fossils bring before us the advent of the great Mesozoic flora and fauna. This group therefore is put at the base of the Mesozoic or Secondary series, though in some regions, as in England, no very satisfactory line of demarcation can always be drawn between Permian and Triassic rocks. The term Trias was suggested by the fact that in Germany the group consists of three well-marked subdivisions. But the old name, New Red Sandstone, is familiarly retained by many geologists in England. The word Trias, like Dyas, is unfortunately chosen, for it elevates a mere local character into an importance which it does not deserve. The threefold subdivision, though so distinct in Germany, disappears elsewhere.

§ 1. General Characters.

As the term Trias arose in Germany, so the development of the Triassic rocks in that and adjoining parts of Europe has been accepted as the normal type of the system. There can be little doubt, however, that though this type is best known, and has been traced in detached areas over the centre and west of Europe, from Saxony to the north of Ireland, reappearing even among the eastern States of North America, it must be looked upon as a local phenomenon. This assertion commends itself to our acceptance, when we reflect upon the nature of the strata of the central European Triassic basins. These rocks consist for the most part of bright red sandstones and clays or marls, with layers, nodules, or veinings of gypsum, beds of rock-salt, bands and massive beds of limestone, often dolomitic. Such an association of materials points to isolated basins of deposit, to which the sea found occasional access, and in which the water underwent concentration, until its gypsum and salt were thrown down. That the intervals of diminished salinity, during which the sea renewed, and perhaps maintained, a connection with the basins, were occasionally of some duration, is shown by the thickness and fossiliferous nature of the limestones.

It is evident, however, that in this, as in all other geological periods, the prevalent type of sedimentation must have been that of the open sea. Though traces of the thoroughly marine equivalents of the red rocks of the basins have been less frequently detected, enough has been observed to reveal some of the general characters of the deposits and life of the Triassic sea. In the Alps masses of limestone and dolomite, with sandstones and shales, attaining a united thickness of many thousand feet, are replete with a marine fauna, in which have been identified organisms that occur also in Triassic rocks of Northern Siberia, the Himalaya Mountains, New Zealand, and the Sierra Nevada on the Pacific slope of North America.

Life.—A more or less marked palæontological break occurs between the top of the Palæozoic and the base of the Mesozoic formations, though this break has been found not to be so complete or universal as was at one time supposed. If the ordinary marine deposits of the time should yet be more extensively discovered and searched, the hiatus would no doubt be still further reduced.

The flora of the Triassic period appears to have consisted

FIG. 358.—TÆNIOPTERIS VITTATA (Brongn.) (½).

FIG. 359.—EQUISETUM COLUMNARE (Brongn.) (½).

mainly of ferns (some of them arborescent), equisetums, conifers, and cycads. Among the ferns a few Carboniferous genera (*Pecopteris*, *Cyclopteris*) still survive, but new forms have appeared—*Anomopteris*,

Acrostichites, Clathropteris, Crematopteris, Sagenopteris. The earliest undoubted horse-tail reeds occur in this system. Here they are represented by the two genera *Equisetum* (Fig. 359) and *Schizoneura.* The latter genus died out in the Jurassic period, but the former is still represented by twenty-five living species. The conifers are represented by *Voltzia,* the cypress-like or spruce-like twigs of which are specially characteristic organisms of the Trias (Fig. 360), and by *Albertia.* But the most distinctive feature in the flora of the earlier Mesozoic ages was the great development of cycadaceous vegetation. The most abundant genus is *Pterophyllum ;* others are *Zamites, Pterozamites, Podozamites, Otozamites.* So typical are these

FIG. 360.—VOLTZIA HETEROPHYLLA (Brongn.).

plants that the Mesozoic formations have been classed as belonging to the "Age of Cycads."

The fauna is exceedingly scanty in the red sandy and marly strata of the central European Trias, and comparatively poor in forms, though often abundant in individuals in the calcareous zones of the same region. From the Alpine development a much more varied suite of organisms has been disinterred. Some of the Alpine limestones are full of foraminifera. Corals abound in some localities in the same rocks. Echinoderms are plentiful among the limestones, particularly crinoid-stems, of which these rocks are in some cases almost wholly composed. One of the most characteristic fossils of

the Muschelkalk is the *Encrinus liliiformis* (Fig. 361). Species of urchins (*Cidaris*) are common in the Alpine Trias. The more frequent brachiopods are species of *Terebratula* (*T. vulgaris*), *Retzia*, *Spirifera*, and *Rhynchonella*. Of the lamellibranchs one of the most distinctively Triassic is *Myophoria* (*M. vulgaris*, *M. Kefersteini*, *M. Whatleyea*); species of *Pecten* (*P. lævigatus*, *P. discites*), *Daonella*,

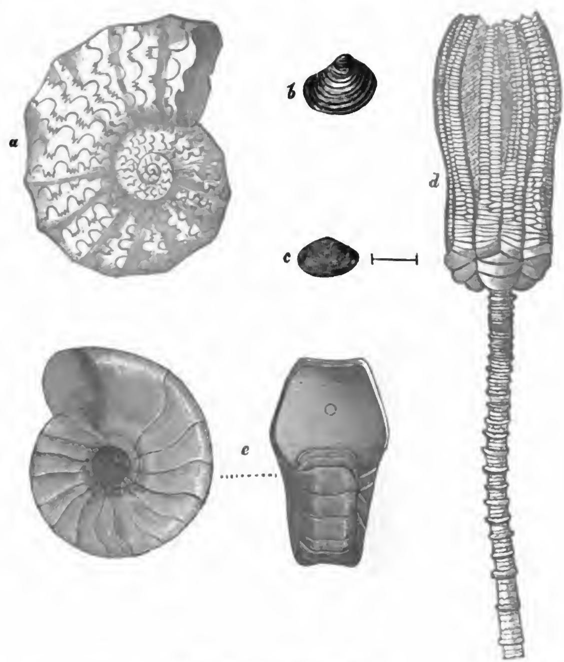

Fig. 361.—Triassic Fossils.

a, Ceratites nodosus (De Haan.); *b*, Estheria minuta (Gold.); *c*, Pullastra arenicola (Strickland) (nat. size and enlarged); *d*, Encrinus liliiformis (Schloth.) (nat. size); *e*, Nautilus bidorsatus (Schloth.) (¼).

Monotis, *Lima*, *Gervillia*, *Avicula*, *Cardium*, *Cardita*, *Nucula*, *Cassianella*, *Pullastra* (Fig. 361) likewise mark different zones in the system. Among gasteropods we find representatives of the genera *Turbo*, *Loxonema*, *Chemnitzia*, *Natica*, *Naticella*, *Turritella*, and others. In no feature is the contrast between the palæontological poverty of the German, and the richness of the Alpine Trias so marked as in

the development of cephalopods in the respective regions. In the former area the nautili are represented chiefly by a few species of *Nautilus* (*N. bidorsatus*, Fig. 361), and the ammonites by species of *Ceratites* (*C. nodosus*, Fig. 361, *C. semipartitus*). In the Alpine limestones, however, there occurs a profusion of cephalopod forms, among which a remarkable commingling of Palæozoic and Mesozoic types is noticeable. The genus *Orthoceras*, so typical of the Palæozoic rocks, has never yet been met with in the German Triassic areas; but it appears in the Alpine Trias in species which do not differ much from those of the older formations. Side by side with these survivals of Palæozoic time we find numerous representatives of the distinctively Mesozoic tribe of *Ammonites*, of which characteristic species are *A.* (*Arcestes*) *Studeri*, *A.* (*Arcestes*) *multilobatus*, *A.* (*Arcestes*) *neortus*, *A.* (*Trachyceras*) *Aon*, *A.* (*Trachyceras*) *Muensteri*, *A.* (*Pinacoceras*) *Metternichii*, *A.* (*Phylloceras*) *Jarbas*, *Ceratites* (several species, but without *C. nodosus*). The fishes of the Triassic period have been but sparingly preserved; among the remains at present known are species of the genera *Gyrolepis*, *Pholidophorus*, *Hybodus*, *Acrodus*, &c. The ancient order of Labyrinthodonts still flourished; numerous prints of their feet have been observed on surfaces of sandstone beds, and the bones of some of them have been found (*Trematosaurus*, *Mastodonsaurus*). Bones and sometimes even nearly entire skeletons of several lacertilian reptiles have also been discovered, the most important genera being *Telerpeton*, *Hyperodapedon*, and *Rhynchosaurus*. The earliest deinosaurs yet known occur in this system (*Thecodontosaurus*, *Teratosaurus*, *Palæosaurus*, *Cladyodon*, &c.).[1] They appear to have walked mainly on their hind legs, the prints of their hind feet occurring in great abundance among the red sandstones of Connecticut. Many of them had three bird-like toes and left foot-prints quite like those of birds. Others had four or even five toes, and attained an enormous size, for a single foot-print sometimes measures twenty inches in length. The earliest forms of crocodiles likewise occur among Triassic rocks in the genera *Stagonolepis* and *Belodon*. It has been supposed that evidence of the existence of Triassic birds is furnished by the three-toed foot-prints just referred to. But probably these are mostly if not entirely the tracks of deinosaurs, the absence of two pairs of prints in each track being accounted for by the bird-like habit of the animals in the use of their hind feet in walking. One of the most noteworthy facts in the palæontology of the Trias is the occurrence in this system of the first relics of mammalian life. These consist of detached teeth and lower jaw-bones, referred to small marsupial animals allied to the *Myrmecobius*, or Banded Ant-eater of New South Wales. The European genus is *Microlestes* (*Hypsiprimnopsis*). In the Trias of North Carolina an allied form has been described under the name of *Dromatherium*.

[1] See on deinosaurs of the Trias, Huxley, *Q. J. Geol. Soc.* xxvi. 32.

§ 2. Local Development.

Britain.[1]—Triassic rocks occupy a large area of the low plains in the centre of England, ranging thence northwards along the flanks of the Carboniferous tracts to Lancaster Bay, and southwards by the head of the Bristol Channel to the south-east of Devonshire. They have been arranged in the following subdivisions :

Rhætic .	Penarth beds.—Red, green, and grey marls, and "White Lias."
Upper Trias or Keuper.	New Red Marl.—Red and grey shales and marls, with beds of rock-salt and gypsum (*Estheria* and *Foraminifera*). Lower Keuper Sandstone.—Thinly laminated micaceous sandstones and marls (waterstones), passing downwards into white, brown, or reddish sandstones, with a base of calcareous conglomerate or breccia.
Middle . .	Wanting in England (Muschelkalk of Germany).
Lower Trias or Bunter.	Upper Mottled Sandstone.—Soft bright-red and variegated sandstones, without pebbles. Pebble-beds.—Harder reddish-brown sandstones with quartzose pebbles, passing into conglomerate; with a base of calcareous breccia. Lower Mottled Sandstone. — Soft bright-red and variegated sandstone, without pebbles.

Like the Permian red rocks below, the sandstones and marls of the Triassic series are almost barren of organic remains. Extraordinary differences in the development of their several members occur, even within the limited area of England, as may be seen from the subjoined table, which shows the variations in thickness from north-west to south-east :

		Lancashire and W. Cheshire.	Staffordshire.	Leicestershire and Warwickshire.
		Feet.	Feet.	Feet.
Keuper.	Red marl	3000	800	700
	Lower Keuper sandstone	450	200	150
Bunter.	Upper mottled sandstone	500	50-200	absent
	Pebble beds	500–750	100–300	0–100
	Lower mottled sandstone	200–500	0–100	absent

Hence we observe that, while towards the north-west the Triassic rocks attain a maximum depth of 5200 feet, they rapidly come down to a fifth or a sixth of that thickness as they pass towards the south-east. South-westwards, however, they swell out in Devon and Somerset to probably not less than 2500 or 3000 feet.[2] Recent borings in the south-eastern counties show that the Triassic rocks are there absent altogether. It is evident that the source of supply of the sediment lay towards the north or north-west. This is further borne out by the character of the pebble-beds. These are coarsest towards the north, and, besides local

[1] See E. Hull, "Permian and Triassic Rocks of England," *Geological Survey Memoirs*, 1869; H. B. Woodward, *Geol. Mag.*; 1874, p. 385; Ussher, *Q. J. Geol. Soc.* xxxii. 367; xxxiv. 459; Etheridge, *Op. cit.* xxvi. 174; A. Irving, *Geol. Mag.* 1874, p. 314; 1877, p. 309; W. T. Aveline, *Op. cit.* 1877, p. 380.

[2] Ussher, *Q. J. Geol. Soc.* xxxii. 392.

materials, contain abundant rolled pebbles of quartz which have evidently been derived from some previous conglomerate, probably from some of the Old Red Sandstone masses now removed or concealed. The Trias rests with a more or less decided unconformability on the rocks underneath it, so that, although the general physical conditions as regards climate, geography, and sedimentation, which prevailed in the Permian period still continued, terrestrial movements had, in the meanwhile, taken place, whereby the Permian sediments were generally upraised and exposed to denudation. Hence the Trias rests now on Permian, now on Carboniferous, and sometimes even on Cambrian rocks. Moreover, the upper parts of the Triassic series overlap the lower, so that the Keuper groups repose successively on Permian and Carboniferous rocks.

The beds of rock-salt in the English Trias have long been profitably worked. The uppermost subdivision of the Keuper, consisting of red marls, has a wide distribution, for it can be traced from the coast of Lancashire to the Bristol Channel, and covers a larger area of surface in the central counties than the rest of the Trias and the whole of the Permian sandstones combined. Even as far south as the coast of Devonshire, it contains casts of the cubical spaces once occupied by crystals of common salt. But in Cheshire the salt occurs in two or more beds, of which the lower is sometimes upwards of 100 feet thick. It is a crystalline substance, usually tinged yellow or red from intermixture of clay and peroxide of iron, but is tolerably pure in the best parts of the beds, where the proportion of chloride of sodium is as much as 98 per cent. Through the bright red marls with which the salt is interstratified there run bands of gypsum, somewhat irregular in their mode of occurrence, sometimes reaching a thickness of 40 feet and upwards. Thin seams of rock-salt likewise occur among the red marls.

As compared with the Trias of Germany and France the most distinctive feature of the English development of the system is the absence of the central calcareous and dolomitic member. It will be observed, indeed, from the foregoing table that a zone of calcareous conglomerate or breccia is frequently observable in central England at the base of the Keuper groups. In the Bristol area a remarkable dolomitic conglomerate, marking a shore line in Triassic times, occupies perhaps the same position. It averages 20 feet in thickness, but rises here and there into cliffs 40 or 50 feet high. It has yielded two genera of Deinosaurs, *Palæosaurus* and *Thecodontosaurus*.[1] (See pp. 486, 493.)

The organic remains of the English Bunter and Keuper are comparatively few, as the conditions for at least animal life must have been extremely unfavourable in the waters of the ancient Dead Sea wherein these red rocks were accumulated. The land possessed a vegetation which, from the fragments yet known, seems to have consisted in large measure of cypress-like coniferous trees (*Voltzia*, *Walchia*), with calamites on the lower more marshy grounds. The red marl group contains in some of its layers numerous valves of the little crustacean *Estheria minuta*, and a solitary species of lamellibranch, *Pullastra arenicola*. A number of teeth, spines, and sometimes entire skeletons of fish have been obtained (*Dipteronotus cyphus*, *Palæoniscus superstes*, *Hybodus Keuperi*, *Acrodus minimus*, *Sphenonchus minimus*, *Lophodus*, &c.). The bones, and

[1] Etheridge, *Q. J. Geol. Soc.* xxvi. 174.

still more frequently the footprints, of labyrinthodont and even of saurian reptiles occur in the Keuper beds—*Labyrinthodon* (4 species), *Cladyodon Lloydii*, *Hyperodapedon*, *Palæosaurus*, *Teratosaurus*, *Thecodontosaurus*, *Rhynchosaurus*, and footprints of *Cheirotherium*. The remains of the small marsupial *Microlestes* have likewise been discovered.

At the top of the Red Marl certain thin-bedded strata form a gradation upwards into the base of the Jurassic system. As their colours are grey and blue, and contrast with the red marls on which they repose conformably, they were formerly classed without hesitation in the Jurassic series. Egerton, however, showed that, from the character of their included fish remains, they had more palæontological affinity with the Trias than with the Lias. Subsequent research, particularly among the Rhætic Alps and elsewhere on the Continent, brought to light a great series of strata of intermediate characters

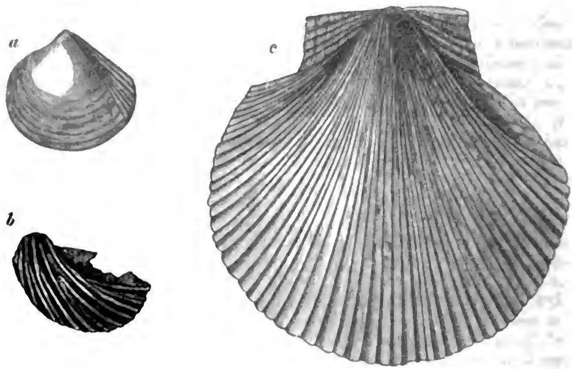

Fig. 362.—Rhætic Fossils.
a, Cardium rhæticum (Merian.); *b*, Avicula contorta (Portlock); *c*, Pecten valoniensis (Defrance).

between the previously recognized Trias and Lias. These results led to renewed examination of the so-called beds of passage in England, which were found to be truly representative of the massive formations of the Tyrolese and Swiss Alps. They are therefore now known as Rhætic, (sometimes as Infra-Lias) and are usually classed as the uppermost member of the Trias, but offering evidence of the gradual approach of the physical geography and characteristic fauna and flora of the Jurassic period.

The Rhætic beds extend as a continuous though very thin band at the top of the Trias, from the coast of Yorkshire across England to Lyme Regis on the Dorsetshire shores. They occur in scattered patches even up as far as Carlisle, and westwards on both sides of the Bristol Channel. Their thickness, on the average, is probably not more than 50 feet, though it rarely increases to 150 feet. They consist of thin-bedded grey

and dark shales and clays, with bands of light-coloured limestone. One of their most important subdivisions is the so-called Bone-bed—a pyritous, micaceous, and occasionally rippled sandstone, sometimes in several bands, abounding in fish bones, teeth, coprolites, and other organic remains. A similar bone-bed reappears on the same horizon in Hanover, Brunswick, and Franconia. The grey marly beds in the lower portion of the series have yielded remains of *Microlestes antiquus* and *M. Rhæticus*. Among the reptilian fossils are some precursors of the great forms which distinguished the Jurassic period (*Ichthyosaurus* and *Plesiosaurus*). The fishes include *Acrodus minimus*, *Ceratodus altus* (and five other species), *Hybodus minor*, *Nemacanthus monilifer*, &c. Some of the lamellibranchs (Fig. 362) are specially characteristic; such are *Cardium Rhæticum*, *Avicula contorta*, *Pecten Valoniensis*, and *Pullastra arenicola*.[1]

Central Europe.—The Trias is one of the most compactly distributed geological formations of Europe. Its main area extends as a great basin from Basel down to the plains of Hanover, traversed along its centre by the course of the Rhine, and stretching from the flanks of the old high grounds of Saxony and Bohemia on the east across the Vosges Mountains into France. This must have been a great inland sea, out of which the Harz Mountains, and the high grounds of the Eifel, Hundsruck, and Taunus probably rose as islands. To the westward of it the Palæozoic area of the north of France and Belgium had been raised up into land.[2] Along the margin of this land red conglomerates, sandstones, and clays were deposited, which now appear here and there reposing unconformably on the older formations. Traces of what were probably other basins occur eastward in the Carpathian district, in the west and south-east of France, and over the eastern half of the Spanish peninsula. But these areas have been considerably obscured, sometimes by dislocation and denudation, sometimes by the overlap of more recent formations. In the region between Marseilles and Nice Triassic rocks cover a considerable area. They contain feeble representatives of the *grès bigarré* or Bunter beds, and of the *marnes irisées* or Keuper division, separated by a calcareous zone believed to be the equivalent of the Muschelkalk of Germany. Their highest platform, the Rhætic or *Infra-Lias*, contains a shell bed abounding in *Avicula contorta*, and is traceable throughout Provence.[3]

In the great German Triassic basin the deposits are as shown in the subjoined table:

Rhætic	Rhætic (Infra-Lias).—Grey sandy clays and fine-grained sandstones, containing *Equisetum*, *Asplenites*, and cycads (*Zamites*, *Pterophyllum*), sometimes forming thin seams of coal—*Cardium Rhæticum*, *Avicula contorta*, *Estheria minuta*, *Nothosaurus*, *Trematosaurus*, *Belodon*, and *Microlestes antiquus*.[4]

[1] Strickland, *Proc. Geol. Soc.* iii. part ii. p. 585. E. B. Tawny, *Q. J. Geol. Soc.* xxii. p. 69; P. B. Brodie, *Op. cit.* p. 93; F. M. Burton, xxiii. p. 315; C. Moore, xvi. p. 483; xxiii. p. 459; xxxvii. pp. 67, 459; W. J. Harrison, xxxii. p. 212; P. M. Duncan, xxiii. p. 12; J. W. Davis, xxxvii. p. 414.

[2] This land, according to MM. Cornet and Briart, rose into peaks 16,000 to 20,000 feet high!

[3] Hébert, *Bull. Soc. Géol. France* (2e *sér.*), xix. p. 100. Dieulafait, *Ann. Sci. Géol.* i. p. 337.

[4] The *Avicula contorta* zone (see Dr. A. von Dittmar, "Die Contorta-Zone," Munich, 1864) ranges from the Carpathians to the north of Ireland and from Sweden to the hills

Keuper.	Bunte Keupermergel, Gypskeuper.—Bright red and mottled marls, with beds of gypsum and rock-salt. In some places where sandstones appear they contain numerous plants (*Equisetum columnare, Pterophyllum*, &c.), and labyrinthodont and fish remains. 300 to 1000 feet.
	Lettenkohle, Kohlenkeuper.—Grey sandstones and dark marls and clays, with abundant plants, sometimes forming thin seams of an earthy hardly workable coal (Lettenkohle). The plants include, besides those above mentioned, the conifers *Araucarioxylon Thuringicum, Voltzia heterophylla*, &c. Some of the shales are crowded with small ostracod crustacea (*Estheria minuta*). Remains of fish (*Ceratodus*) and of the *Mastodonsaurus Jægeri* have been obtained. About 230 feet.
Muschelkalk.	Upper Limestone (true Muschelkalk) in thick beds with argillaceous partings.—It abounds in organic remains, among which *Nautilus bidorsatus, Lima striata, Myophoria vulgaris, Trigonodus Sandbergeri*, and *Terebratula vulgaris* are specially characteristic, with *Encrinus liliiformis* in the lower and *Ceratites nodosus* in the upper part of the rock. It is a marine formation, sometimes almost wholly made up of crinoid stems. 200 to 400 feet.
	Middle Limestone and Anhydrite, consisting of dolomites with anhydrite, gypsum, and rock-salt. Nearly devoid of organic remains, though bones and teeth of saurians have been found. 200 to 400 feet.
	Lower Limestone (Wellenkalk), consisting of limestones and dolomites, but on the whole poor in fossils, save in the limestone bands, some of which form a lower zone full of *Encrinus liliiformis*, while a higher zone is characterized by *Myophoria orbicularis*. 160 to 500 feet.
Bunter.	Upper (Röth).—Red and green marls, with gypsum in the lower part. 250 to 300 feet. (*Myophoria costata.*)
	Middle.—Coarse-grained sandstones, sometimes incoherent (*Voltzia*-sandstones), with wayboards of *Estheria*-shale.
	Lower.—Fine reddish argillaceous sandstone (Grès des Vosges), often micaceous and fissile, with occasional interstratifications of dolomite and of the marly oolitic limestone called "Rogenstein."
	The Bunter division is usually barren of organic remains. The plants already known include *Equisetum arenaceum*, one or two ferns, and a few conifers (*Albertia* and *Voltzia*). The lamellibranch *Myophoria costata* is found in the upper division all over Germany. Numerous footprints occur on the sandstones, and the bones of labyrinthodonts as well as of fish have been obtained.

Alpine Trias.[1]—The Trias attains an enormous development in the eastern Alps, where it bears evidence of having originated under very different conditions from those of the Trias in Germany. The great thickness of its limestones, and their unequivocally marine organisms, show that it must have accumulated in opener water, which remained clear and comparatively free from inroads of sandy and muddy sediment. It possesses, moreover, a high interest as being a massive formation of marine origin formed between Permian and Jurassic times, and containing, as already stated, a remarkable blending of true Palæozoic organisms with others as characteristically Mesozoic. Including the Rhætic deposits it is divided into three great series:

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of Lombardy. In northern and western Europe it forms part of a thin littoral or shallow-water formation, which over the region of the Alps expands into a massive calcareous series, which accumulated in a deeper and clearer sea. It is well developed also in northern Italy. See Stoppani, "Géologie et Paléontologie des Conches à Avicula Contorta en Lombardie," Milan, 1881. On the plants of the Rhætic beds of Scania, see G. de Saporta, *Ann. Sci. Géol.* (1877).

[1] See Gümbel, "Geog. Beschreib. des Bayerisch. Alpen," 1861; Stur, "Geologie der Steiermark," 1871; E. von Mojsisovics, *Jahrb. Geol. Reichsanstalt.* Vienna, 1869, 1874, 1875, and "Dolomitriffe Südtirols und Venetiens," 1878, and memoirs by Richthofen, Von Hauer, Laube, Süss, and others in the *Jahrb. Geol. Reichsanstalt.*; Von Hauer's "Die Geologie," p. 358, *et seq.*

Rhætic—a massive group of marine limestones and dolomites, with occasional zones of shale, but no sandstones.

Kössen beds (Gervillia beds, Azzarola group of Lombardy).—Dark marly shales. Fossils chiefly small lamellibranchs and brachiopods.

Dachstein Limestone (Megalodus-kalk).—Large species of *Megalodus*; some beds are coral-reefs; certain limestone bands (Starhemberg-beds) are crowded with fossils, especially brachiopods like those of the Kössen beds.

Dachstein Dolomite (Haupt Dolomit, Opponitzer Dolomit, Seefelder Dolomit, Dolomia media of Italy).—A pale, well-bedded, finely crystalline rock, splitting into angular fragments in weathering, usually unfossiliferous, but where it passes into limestone sometimes full of large bivalves (*Megalodus triqueter*).

Upper Trias—a series of exceedingly variable formations, attaining sometimes a depth of thousands of feet, with associated eruptive rocks (well seen round the Lake of Lugano, and near Botzen, in South Tyrol), consisting of monzonite, tourmaline-granite, melaphyre, augite-porphyry, syenite-porphyry, and interstratified tuffs.

3rd series of shaly, sandy, and marly rocks, comprising in different localities the following groups of strata—

- Cardita beds, with numerous fossils. Limestone-Alps of North Tyrol.
- Gorno and Dossena beds. Lombardy Alps.
- Raibl-beds—shales, marls, &c., comprising abundant organisms (plants, crustaceans, cephalopods, fishes); Southern Carinthia.

2nd series of calcareous and dolomitic rocks, with varying local development—

- Pötschen Limestone, containing fossils like those of the Hallstatt Limestone.
- Hallstatt Limestone—a red and mottled marble which in the Salzkammergut lies on the Zlambach beds. Its fossils, chiefly cephalopods, some of them of gigantic size, are among the most interesting of the Alpine Trias.
- Wetterstein Limestone and Dolomite, in North Tyrol and the Bavarian Alps, lying on the Partnach beds.
- Esino Limestone, characterized by its large gasteropods, numerous lamellibranchs, and cephalopods.
- Schlern Dolomite, a white saccharoid rock, containing chiefly foraminifera, 3280 feet thick, forming picturesque groups of mountains (*Diplopora annulata*, *Chemnitzia*, *Natica*).

1st series of shaly and marly formations—

- Lunz beds, containing seams of coal and abundant terrestrial plants, and forming the only known fresh-water group in the upper Alpine Trias.
- Partnach beds, dark, poorly fossiliferous shales.
- Zlambach beds—marls and hornstone-like limestone, containing an abundant fauna with large cephalopods, lamellibranchs, and numerous corals.
- St. Cassian beds—calcareous marls lying at St. Cassian, South Tyrol, above the Wengen beds, and marked by their extraordinarily rich fauna (37 ammonites, 3 orthoceratites, 205 gasteropods, 70 lamellibranchs, 33 brachiopods, 29 echini, 10 crinoids, 42 corals, and 36 sponges are described).
- Wengen beds—dark shales and tuff-sandstones with *Daonella* (*Halobia*) *Lommeli*, *Posidonomya Wengensis*, and Ammonites of the *Trachyceras* group, resting on the tuffaceous and siliceous Buchenstein beds.

Lower Trias—a much thinner series than the Upper.

2nd. Virgloria Limestone (Wellenkalk) or Alpine Muschelkalk—a series of limestones and dolomites composed of the following groups—

- *b.* Cephalopod Limestone (Reiflinger Kalk), with numerous cephalopods (*Ammonites* (*Arcestes*) *Studeri*, *Ceratites binodosus*).
- *a.* Brachiopod Limestone (Recoarokalk), distinguished by the number of its brachiopods (*Retzia trigonella*, *Spiriferina Mentzeli*, &c.).

1st. Werfen (Gröden) Sandstones and Guttenstein Limestone (Seisser, Campiler Schichten). (*Pleuromya fassaensis*, *Posidonomya Clarai*, *Avicula venetiana*, *Naticella costata*, *Turbo rectecostatus*, *Ceratites cassianus*, &c.). These beds may be paralleled with the Röth or uppermost division of the German Bunter.

The lower division of the Alpine Trias ranges through nearly the whole mountain-chain, presenting everywhere the same general petrographical and palæontological characters. Hence it has been an invaluable datum-line from which to unravel the complicated structure of that region.

North America.—Rocks which are regarded as equivalent to the European Trias cover a large area in North America. On the Atlantic coast they are found in Prince Edward's Island, New Brunswick and Nova Scotia, in Connecticut, New York, Pennsylvania, and North Carolina. Spreading over an enormous extent of the western territories, they cross the Rocky Mountains into California and British Columbia. They consist mainly of red sandstones, passing sometimes into conglomerates, and often including shales and impure limestones. A distinction may be drawn between the system as developed in the eastern and central parts of the continent on the one hand and along the Pacific slope on the other. In the former wide region the rocks, evidently laid down in inland basins like those of the same period in Europe, are remarkably barren of organic remains. Their fossil contents include remains of terrestrial vegetation with footprints and other traces of reptilian life, but with hardly any indications of the presence of the sea.

The fossil plants present a general facies like that of the European Triassic flora, among them cycads, including some of the European species of *Pterophyllum.* Ferns (*Pecopteris, Neuropteris, Clathropteris*), calamites, and conifers are the predominant forms. The fauna is remarkable chiefly for the number and variety of its vertebrates. The labyrinthodonts are represented by footprints, from which upwards of fifty sp cies have been described. Saurian footprints have likewise been recognized; in a few cases their bones also have been found. Some of the vertebrates had birdlike characteristics, among others that of three-toed hind feet, which produced impressions exactly like those of birds. But as already remarked, it is by no means certain that what have been described as "ornithichnites" were not really made by deinosaurs. The small insectivorous marsupial (*Dromatherium*), above referred to, found in the Trias of North Carolina, is the oldest American mammal yet known.

On the Pacific slope, however, a very different development of the Trias occurs. The strata are estimated to attain a thickness of sometimes as much as 14,000 or 15,000 feet. They contain distinctly marine organisms, which include a mingling of such Palæozoic genera as *Spirifera*, *Orthoceras*, and *Goniatites*, with characteristically Secondary forms, as ammonites (*Ceratites Haidingeri*, *Ammonites ausseanus*, &c.) and bivalves of the genera *Halobia*, *Monotis*, *Myophoria*, &c.

Asia.—The Trias has a wide extension in this continent. Strata with *Ceratites* and *Orthoceratites* occur in Beloochistan, and in the Salt Range of the Punjaub. In northern Kashmir and western Tibet a well-developed succession of Triassic formations occurs among the Himalayan ranges, sometimes exceeding 4000 feet in thickness. It contains many of the same species of fossils as occur in the Alpine Trias. Some of its forms are *Ammonites floridus*, *A. diffusus*, *Halobia Lommeli*, *Monotis salinaria*, *Megalodon triqueter*, while the fresh-water beds (*Karharbári*) in the Gondwana series of India contain a distinctly Bunter assemblage of plants, including *Voltzia heterophylla* and *Albertia* (near *A. speciosa*).[1]

[1] Medlicott and Blanford's "Geology of India," pp. xlvi. 114.

Australia.—In New South Wales, Victoria, and Queensland an important coal-bearing series of strata occurs, containing a flora which has many affinities with that of the Trias of Europe and of Asia. Among its plants are species of *Cyclopteris*, *Gangamopteris*, *Glossopteris*, *Odontopteris*, *Pecopteris*, *Sphenopteris*, *Tæniopteris*, and *Zamites*.

Section II.—Jurassic System.

The position of this great series of fossiliferous rocks was first recognized in the geological series in England by William Smith, and received the name of "Oolitic" from the frequent and characteristic oolitic structures of many of its limestones. Lithological names being, however, objectionable, the term "Jurassic," applied by the geologists of France and Switzerland to the great development of the rocks among the Jura Mountains, has now been universally adopted.

§ 1. General Characters.

Jurassic rocks have been recognized over a large part of the world. But they no longer present that general uniformity of lithological character so marked among the Palæozoic systems. The suite

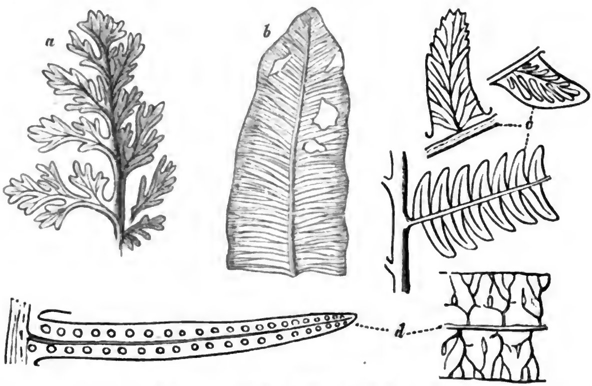

FIG. 363.—JURASSIC FERNS (Lower Oolite).
a, Sphenopteris trichomanoides (Brongn.); *b*, Tæniopteris major (Lindl. and Hutt.) (½); *c*, Pecopteris dentatus (Lindl. and Hutt.) (nat. size and mag.); *d*, Phlebopteris polypodiodes (Brongn.) (nat. size and mag.).

of rocks changes as it passes from England across France, and is replaced by a distinctly different type in Northern Germany and by another in the Alps. If we trace the system further into the Old

World we find it presenting still another aspect in North-Western India, while in America the meagre representatives of the European development have again a facies of their own. Hence no generally applicable petrographical characters can be assigned to this part of the geological record.

The **flora** of the Jurassic period, so far as known to us, was essentially gymnospermous. The Palæozoic forms of vegetation traceable up to the close of the Permian system are here entirely absent. Equisetums, so common in the Trias, are still abundant, one of them (*E. arenaceum*) attaining gigantic proportions. Ferns likewise continue plentiful, some of the chief genera being *Alethopteris*, *Sphenopteris*, *Phlebopteris*, and *Oleandridium* (*Tæniopteris*). The Cycads, however, are the dominant forms, in species of *Zamites*,

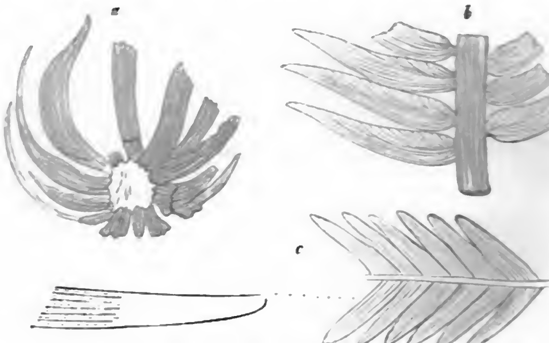

FIG. 364.—JURASSIC CYCADS (Lower Oolite).
a, Williamsonia (Zamia) gigas (Carr) (¼); *b*, Cycadites lanceolata (Lindl. and Hutt.) (½); *c*, Cycadites (Pterophyllum) pectinoides (Phill.) (nat. and mag.).

Pterophyllum, *Anomozamites*, *Pterozamites*, *Dioonites*, *Podozamites*, *Sphenozamites*, *Glossozamites*, *Otozamites*, *Cycadites*, *Clathraria*, *Cycadeoidea*, *Zamiostrobus*, *Beania*, *Cycadospadix*, *Cycadinocarpus*. Conifers also are found in some numbers, particularly Araucarians of the genera *Pachyphyllum* and *Araucaria*, also *Pinites*, *Brachyphyllum*, and *Thuyites*.

The Jurassic **fauna** presents a far more varied aspect than that of any of the preceding systems. Owing to the intercalation of numerous fresh-water, and sometimes even terrestrial, deposits among the marine formations, traces of the life of the lakes and rivers, as well as of the land itself, have been to some extent embalmed, besides the preponderant marine forms. The conditions of sedimentation have likewise been favourable for the preservation of a succession of varied phases of marine life. Professor Phillips

has directed attention to the remarkable ternary arrangement of the English Jurassic series.[1] Argillaceous sediments are there succeeded by arenaceous, and these by calcareous, after which the argillaceous once more recur. No fewer than five repetitions of this succession are to be traced from the top of the Lias to the top of the Portlandian. Such an alternation of sediments points to interrupted depression of the sea bottom.[2] It permitted the growth and preservation of different kinds of marine organisms in succession over the same areas,—at one time sand-banks followed by a growth of coral reefs, with abundant sea-urchins and shells, and then by an inroad of fine mud, which destroyed the coral-reefs, but in which, as it sank to the bottom, the abundant cephalopods and other molluscs of the time were admirably preserved.

A characteristic feature of the Jurassic fauna is the abundance of its beds or reefs of coral. During the time of the Corallian formation in particular the greater part of Europe appears to have

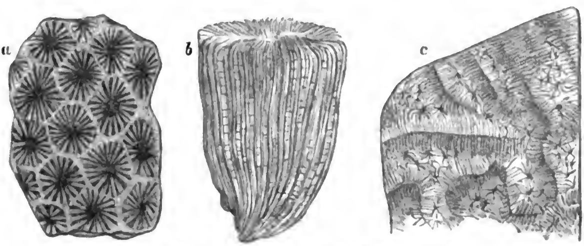

FIG. 365.—JURASSIC CORALS (Middle Oolite).
a, Isastræa helianthoides (Goldf.); *b*, Montlivaltia dispar (Phill.); *c*, Comoseris irradians (M. Edw.).

been submerged beneath a coral sea. Stretching through England from Dorsetshire to Yorkshire, these coral accumulations have been traced across the Continent from Normandy to the Mediterranean, and through the east of France and the whole length of the Jura Mountains, and along the flank of the Swabian Alps. The corals belonged to the genera *Isastræa*, *Thamnastræa*, *Thecosmilia*, *Montlivaltia*, &c. (Fig. 365). Echinoderms were abundant, particularly crinoids of the genera *Pentacrinus*, *Extracrinus* (Fig. 366), and *Apiocrinus*, several forms of star-fishes, and numerous urchins, among which the genera *Acrosalenia*, *Cidaris* (Fig. 367), *Diadema*, *Echinobrissus*, *Hemipedina*, *Pseudodiadema*, *Clypeus*, *Pygaster*, and *Pygurus* were conspicuous. The brachiopods yet found are chiefly species of *Rhynchonella* and *Terebratula* (Fig. 369); the last of the ancient group of *Spirifers* and of the genus *Leptæna* (Fig. 368) disappear in the Lias. Among the lamellibranchs some of the more abun-

[1] *Geology of Oxfordshire*, &c., p. 393. [2] *Ante*, p. 498.

dant genera are *Avicula*, *Gervillia*, *Gryphæa*, *Exogyra*, *Lima*, *Monotis*, *Ostrea*, *Pecten*, *Pinna*, *Astarte*, *Cardinia*, *Cardium*, *Gresslya*, *Hippopodium*, *Modiola*, *Myacites*, *Pholadomya*, and *Trigonia*. Some of these genera, particularly the tribe of oysters, are specially charac-

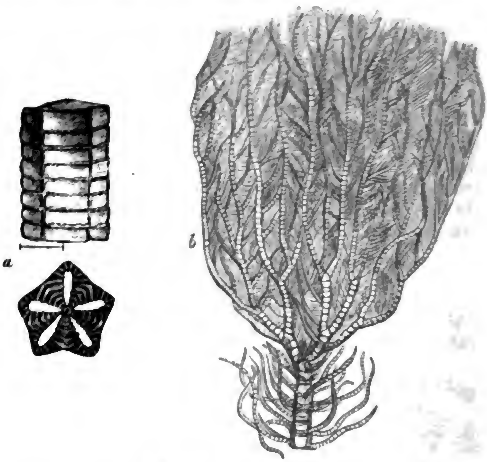

Fig. 366.—Lias Crinoids.
a, Pentacrinus basaltiformis (Goldf.) (side view and end view of part of stem); *b*, Extracrinus briareus (Mill.)(½).

teristic, *Gryphæa*, for example, occurring in such numbers in some of the Lias limestones as to suggest for these strata the name of "Gryphite Limestone." Different species of *Trigonia*, a genus now restricted to the Australian seas, are likewise distinctive of horizons in the middle and upper part of the system. Many of the most abundant gasteropods belong to still living genera, as *Cerithium*, *Natica*, *Purpura*. But the most important element in the molluscan fauna was undoubtedly supplied by the cephalopods. In particular the tetrabranchiate tribe of Ammonites attained an extraordinary exuberance, both in number of individuals and in variety of form (see Figs. 383–7). The dibranchiate division was likewise represented by species of cuttle-fish (*Teudopsis*, *Beloteuthis*, *Sepia*, but particularly *Belemnites*, which is the preponderating type). No contrast can be more marked than between the crustacean fauna of the Jurassic

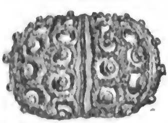

Fig. 367.—Jurassic Urchin.
Cidaris florigemma (Phill.)—Corallian.

and that of the older systems. The ancient trilobites and eurypterids, as remarked by Phillips, are here replaced by tribes of long-tailed ten-footed lobsters and prawns, and of representatives of our modern crabs.

Here and there, particularly in the Jurassic series of England and Switzerland, thin bands occur containing the remains of terrestrial insects. The neuropterous forms predominate, including remains

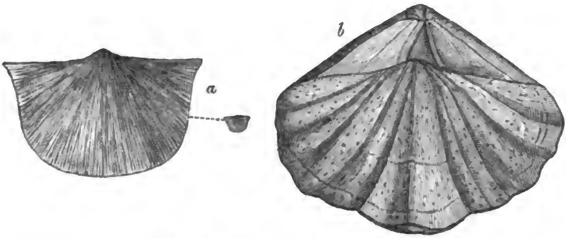

FIG. 368.—LIAS BRACHIOPODS.
a, Leptæna Moorei (Dav.)(nat. size and enlarged); *b*, Spiriferina Walcottii (Sby.).

of dragon-flies and may-flies. There are also cockroaches and grasshoppers. The elytra and other remains of numerous beetles have been obtained belonging to still familiar types (*Curculionidæ, Elateridæ, Melolonthidæ*). The wing of a butterfly (*Palæontina oolitica*) obtained from the Stonesfield Slate is interesting as being the oldest known butterfly. Its nearest living allies are essentially tropical American forms.[1] Some of the more important genera of

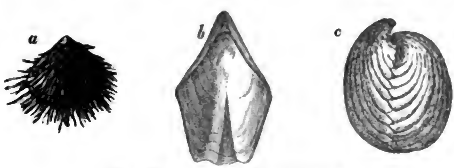

FIG. 369.—OOLITIC BRACHIOPODS.
a, Rhynchonella spinosa (Schloth.) (½) Lower Oolite; *b*, Terebratula Phillipsii (Mor.) (½), Lower Oolite; *c*, Rhynchonella pinguis (Rœm.?), Middle Oolite.

fishes are *Acrodus, Æchmodus, Dapedius, Hybodus, Lepidotus, Leptolepis, Pholidophorus, Pycnodus, Saurichthys, Semionotus, Strephodus, Ischyodus.*[2]

The most impressive feature in the life of the Jurassic period is

[1] A. G. Butler, *Geol. Mag.* x. (1873), p. 2; i. 2nd ser. (1874), p. 446.
[2] For a list of Liassic fishes, see memoir by H. E. Sauvage, *Ann. Sciences Géol.* vi. (1875).

the abundance and variety of the reptilian forms. Mesozoic time has been termed the "Age of Reptiles," for it witnessed the maximum development of reptilian types with the rise and growth of whole orders of reptiles which have long since been extinct. The

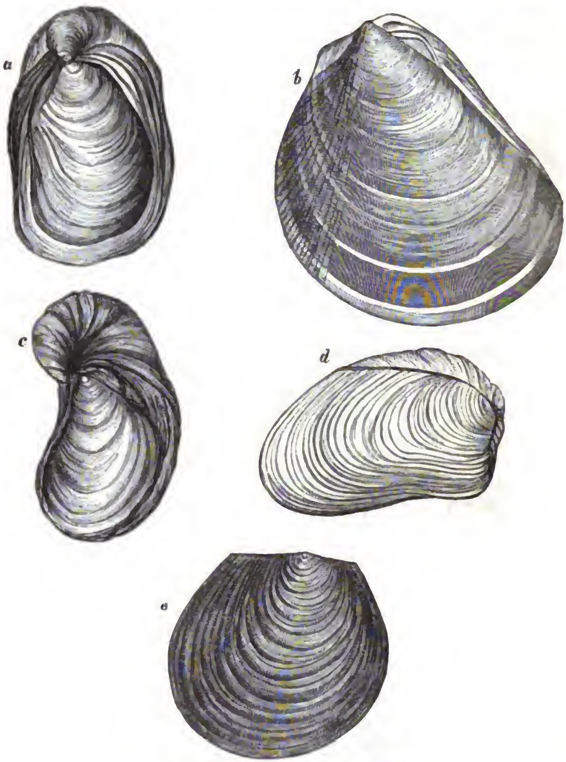

Fig. 370.—Liassic Lamellibranchs.

a, Gryphæa cymbium (Lam.) ($\frac{1}{3}$); *b*, Lima gigantea (Sby.) ($\frac{1}{3}$); *c*, Gryphæa incurva (Sby.) ($\frac{2}{3}$); *d*, Hippopodium ponderosum (Sby.) ($\frac{1}{4}$); *e*, Posidonia Bronnii (Goldf.) (nat. size).

first true turtles seem to have made their appearance during this period. Numerous fragments of lacertilians have been obtained. Most abundant are the bones of various crocodilian genera, such as *Teleosaurus, Steneosaurus,* and *Goniopholis. Teleosaurus,* which occurs

in the Yorkshire Lias and the Stonesfield Slate, was a true carnivorous crocodile, measuring about 18 feet in length, and is judged by Phillips to have been in the habit of venturing more freely to sea than the gavial of the Ganges or the crocodile of the Nile. Of the long extinct reptilian types one of the most remarkable was that of the enaliosaurs or sea-lizards. One of these, the *Ichthy-*

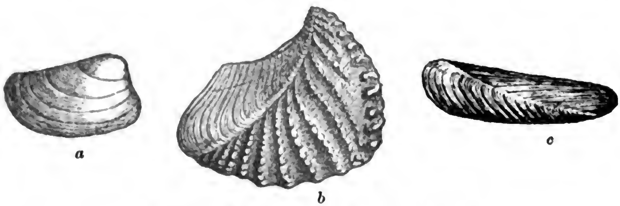

FIG. 371.—LOWER OOLITIC LAMELLIBRANCHS.
a, Nucula Hammeri (Defr.); *b*, Trigonia navis (Lam.) (½); *c*, Mytilus sowerbyanus (D'Orb.) (½).

osaurus (Fig. 377, *a*), was a creature with a fish-like body, two pairs of strong swimming paddles, probably a vertical tail-fin, and a head joined to the body without any distinct neck, but furnished with two large eyes, having a ring of bony plates round the eyeball, and with teeth that had no distinct sockets. Some of the skele-

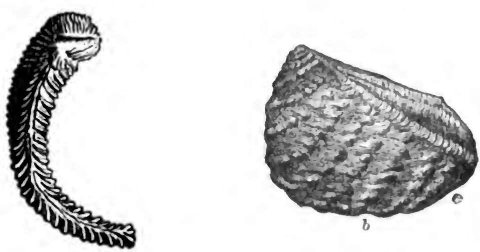

FIG. 372.—MIDDLE OOLITIC LAMELLIBRANCHS.
a, Ostrea hastellata (Schloth.) (½); *b*, Trigonia clavellata (Sby.) (½).

tons of this creature exceed 24 feet in length. Contemporaneous with it was the *Plesiosaurus* (Fig. 377, *b*), distinguished by its long neck, the larger size of its paddles, the smaller size of its head, and the insertion of its teeth in special sockets, as in the higher saurians. These creatures seem to have haunted the shallow seas of the Liassic time, and, varying in species with the ages, to have survived till

towards the close of Mesozoic time.[1] Another genus, *Pliosaurus*, related to the last-named, was distinguishable from it by the shortness of its neck and the proportionately large size of its head. Another extraordinary reptilian type was that of the pterosaurians or flying reptiles, which were likewise peculiar to Mesozoic time. Those huge winged bat-like creatures had large heads, teeth in distinct sockets, eyes like the *Ichthyosaurus*, one finger of each fore foot prolonged to a great length, for the purpose of supporting a membrane for flight, and bones, like those of birds, hollow and air-filled.[2] The best known genus, *Pterodactylus* (Fig. 378), had a short tail and jaws furnished from end to end with long teeth. Others were *Dimorphodon*, distinguished especially by the length

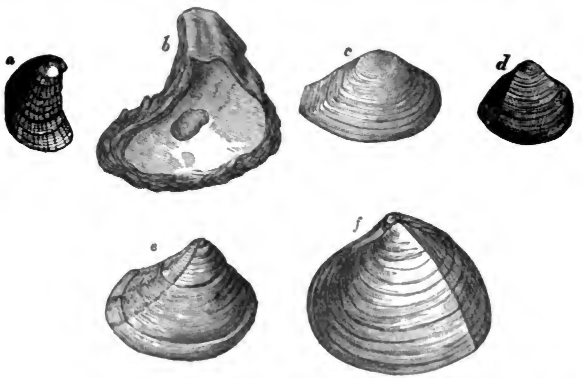

Fig. 373.—Upper Oolitic Lamellibranchs.

a, Exogyra (Ostrea) virgula (D'Orb.); *b*, Ostrea deltoidea (Sby.) ($\frac{1}{4}$); *c*, Astarte Hartwellensis (Sby.) ($\frac{1}{1}$); *d*, Cardium striatulum (Sby.) ($\frac{1}{2}$); *e*, Trigonia gibbosa (Sby.) ($\frac{1}{2}$); *f*, Cardium dissimile (Sby.) ($\frac{1}{2}$).

of its tail, and *Rhamphorhynchus* (Fig. 379), also possessing a long tail, with a caudal membrane and having formidable jaws, which may have terminated in a horny beak. These strange harpy-like creatures were able to fly, to shuffle on land, or perch on rocks, perhaps even to dive in search of their prey. Lastly, the most colossal living beings of Mesozoic time, and, indeed, so far as we know, of any time, belonged to the extinct order of Deinosaurs, in

[1] On the distribution of the Plesiosaurs see a useful table by G. F. Whidborne *Q. J. Geol. Soc.* 1881, p. 480.

[2] See Marsh on wings of Pterodactyles, *Amer. Journ. Sci.* April 1882. The remarkable specimen of *Rhamphorhynchus* (*R. phyllurus*) from the Solenhofen Slate, described by this author, possessed a long tail, the last sixteen short vertebræ of which supported a peculiar caudal membrane which, kept in an upright position by flexible spines, must have been an efficient instrument for steering the flight of the creature.

which the ordinary reptilian characters were united to others, particularly in the hinder part of the skeleton, like those of birds. Among the Jurassic deinosaurs the most important European genera are *Compsognathus*, *Megalosaurus* (Fig. 379), and *Ceteosaurus*. In *Compsognathus*, from the Solenhofen Limestone, the bird-like affinities are strikingly exhibited, as it possessed a long neck, small head, and long hind limbs on which it must have hopped or walked. The *Megalosaurus* of the Stonesfield Slate is estimated to have had a length of 25 feet, and to have weighed two or three tons. It frequented the shores of the lagoons, walking probably on its massive hind legs, and feeding on the molluscs, fishes, and perhaps the small mammals of the district. Still more gigantic was the *Ceteosaurus*,

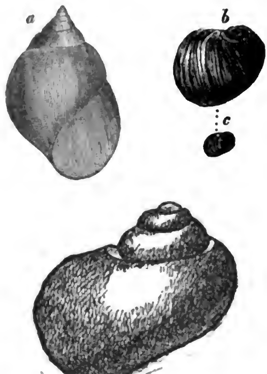

FIG. 374.—JURASSIC GASTEROPODS.
a, Natica hulliana (Lyc.) (Lower Oolite); b, Nerita costulata (Desh.) (Lower Oolite, nat. size and mag.); c, Natica globosa (Rœm.) (Upper Oolite).

which, according to Phillips, probably reached when standing a height of not less than 10 feet and a length of 50 feet. It seems to have been a marsh-loving or river-side animal, living on the ferns, cycads, and conifers among which it dwelt. But these monsters of the Old World were surpassed in dimensions by some discovered in recent years by Professor Marsh in the Jurassic beds of Colorado. In particular the *Atlantosaurus* was built on so huge a scale that its femur alone is more than 8 feet high. The corresponding bone of the most gigantic elephant looks like that of a dwarf when put beside this fossil. The whole length of the animal is supposed to have been not much short of 100 feet, with a height of 30 feet or more. Contemporaneous with these huge creatures, however, there existed in Jurassic time in North America diminutive forms having such

strong avian affinities that their separate bones cannot be distinguished from those of birds. Professor Marsh, who has brought

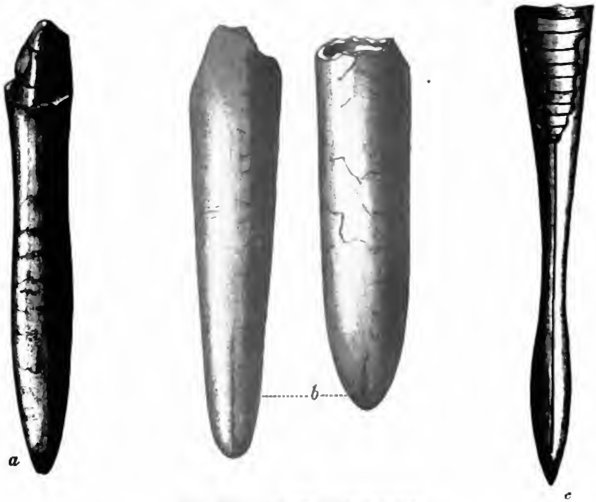

FIG. 375.—JURASSIC BELEMNITES.
a, Belemnites paxillosus (Schloth.) (Lias, ½); *b*, B. irregularis (Schloth.) (Lias, nat. size); *c*, B. hastatus (Blainv.) (Middle Oolite, ½).

these interesting forms to light, regards them as having been in some cases probably arboreal in habit, with possibly at first no more

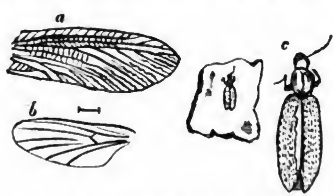

FIG. 376.—INSECTS, PURBECK BEDS.
a, *b*, Wings of Neuropterous insects (*Corydalis*) (nat. size and mag.); *c*, *Carabus elongatus* (nat. size and mag. Brodie, Foss. Insects, pl. ii. and v.).

essential difference from the birds of their time than the absence of feathers.[1]

[1] *Amer. Journ. Sci.* xxli. (1880), p. 340. See also Carl Vogt, *Rev. Scientif.* Sept. 1879; Seeley, *Geol. Mag.* 1881, 300, 454.

The oldest known bird, *Archeopteryx* (Fig. 380), comes from the

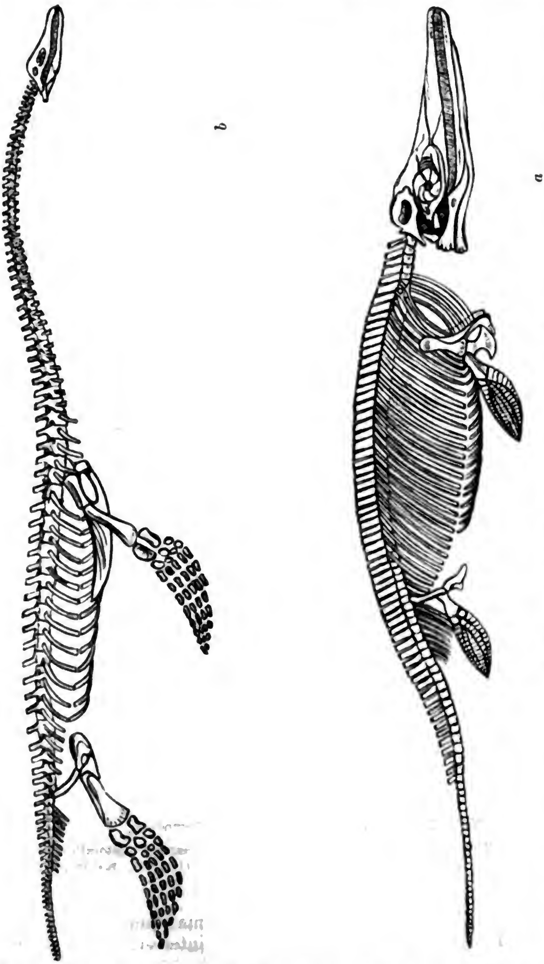

FIG. 377.—JURASSIC ENALIOSAURS OR SEA-LIZARDS.
a, Ichthyosaurus communis (Conyb.) (restored by Conybeare and Cuvier); *b*, Plesiosaurus dolichodeirus (Conyb.) (restored by Conybeare).

Solenhofen Limestone in the Upper Jurassic series. This interesting form united some of the characters of reptiles with those of a true

bird. Thus it possessed biconcave vertebræ, a well-ossified broad sternum, three fingers only in each toe, all ending in a claw, a long lizard-like tail, each vertebra of which bore a pair of quill-feathers,

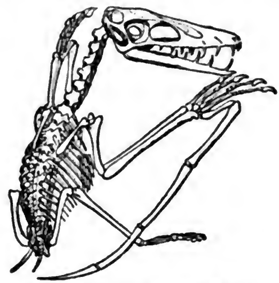

FIG. 378.—JURASSIC PTEROSAUR.
Pterodactylus crassirostris (Goldf.) (Middle Oolite).

the wings had free claws, and the jaws carried true teeth as in the toothed birds found in the Cretaceous rocks of Kansas.[1]

The most highly organized animals of which the remains have

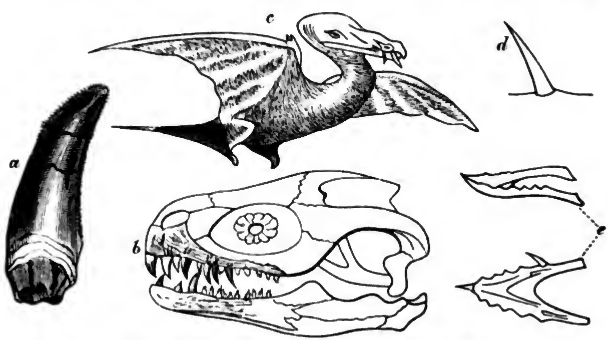

FIG. 379.—JURASSIC DEINOSAUR AND PTEROSAUR.

a, Megalosaurus Bucklandi (Meyer), tooth ($\frac{1}{2}$); *b*, Megalosaurus, restoration of head, after Owen ($\frac{1}{10}$); *c*, Rhamphorhynchus Bucklandi (Goldf.), restoration, after Phillips; *d*, Do. tooth (nat. size); *e*, Do. jaw ($\frac{1}{2}$).

been discovered in the Jurassic system are small marsupials. Two horizons in England have furnished these interesting relics—the Stonesfield Slate and the Purbeck beds. The Stonesfield Slate has

[1] See Marsh, *Amer. Journ. Sci.* Nov. 1881, p. 337.

yielded the remains of four genera—*Amphilestes* and *Phascolotherium* (Fig. 381), probably insectivorous, the latter being related to the living American opossums; *Amphitherium*, resembling most closely the Australian *Myrmecobius;* and *Stereognathus*, which Owen is disposed to think was rather a placental, hoofed, and herbivorous form. Higher up in the English Jurassic series another interesting group of mammalian remains has been obtained from the Purbeck beds, whence upwards of twenty species have been exhumed belonging to eleven genera (*Spalacotherium, Amblotherium, Peralestes, Achyrodon, Peraspalax, Peramus, Stylodon, Bolodon, Triconodon, Triacanthodon*), of which some appear to have been insectivorous, with their closest

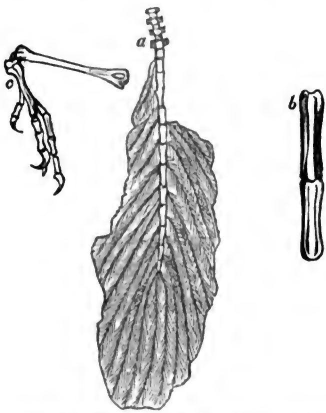

FIG. 380.—BIRD (ARCHÆOPTERIX MACRURA) (Owen)—SOLENHOFEN LIMESTONE (Middle Jurassic).
a, Tail and tail-feathers (¼); *b*, Caudal vertebræ (nat. size); *c*, foot (¼).

living representatives among the Australian phalangers and American opossums, while one, *Plagiaulax*, resembling the Australian kangaroo rats (*Hypsiprymnus*), is held by Owen to have been a carnivorous form.[1]

§ 2. Local Development.

The Jurassic system covers a vast area in Europe. Beginning at the west, remnants of it occur in the far north-west of Scotland. It ranges across England as a broad band from the coasts of Yorkshire to those of Dorset. Crossing the Channel it encircles with a great ring the Cretaceous and Tertiary basin of the north of France, whence it ranges on the one side southwards down the valleys of the Saone and Rhone, and on

[1] See Falconer, *Q. J. Geol. Soc.* xiii. 261; xviii. 348; Owen, *Monograph of Mes. Mammals: Palæontograph. Soc.* 1871.

the other round the old crystalline nucleus of Auvergne to the Mediterranean. Eastwards it sweeps through the Jura Mountains (whence its name is taken) up to the high grounds of Bohemia. It forms part of the outer chains of the Alps on both sides, rises along the centre of the Apennines, and appears here and there over the Spanish peninsula. Covered by more recent formations it underlies the great plain of northern Germany, whence it ranges eastwards and occupies large tracts in central and eastern Russia. According to Neumayr,[1] three distinct geographical regions of deposit can be made out among the Jurassic rocks of Europe. (1.) The Mediterranean province, embracing the Pyrenees, Alps, and Carpathians, with all the tracts lying to the south. One of the biological characters of this area was the great abundance of ammonites belonging to the groups of *Heterophylli* (*Phylloceras*) and *Fimbriati* (*Lytoceras*), and the presence of forms of *Terebratula* of the family of *T. diphya* (*janitor*). (2.) The central European province, comprising the tracts lying to the north of the Alpine ridge, including France, England, Germany, and the Baltic countries, and marked by the comparative rarity of the ammonites just mentioned, which are replaced by others of the genera *Aspidoceras* and *Oppellia*, and by abundant reefs and masses of coral. (3.) The boreal or Russian province, comprising the middle and north of Russia, Petschora, Spitzbergen, and Greenland. The life in this

Fig. 381.—Marsupial from the Stonesfield Slate.
Phascolotherium Bucklandi (Broderip.); *a*, teeth, magnified; *b*, jaw, nat. size.

area was less varied than in the others, in particular, the widely distributed species of *Oppellia* and *Aspidoceras* of the middle-European province are absent, as well as large masses of corals, showing that in Jurassic times there was a perceptible diminution of temperature towards the north.

Britain.[2]—The stratigraphical succession of the Jurassic rocks was first worked out in England by William Smith, in whose hands they were made to lay the foundations of stratigraphical geology. The names adopted by him for the subdivisions he traced across the country have

[1] Neumayr, *Jura-Studien, Jahrb. Geol. Reichsanstalt.* 1871, pp. 297, 451; *Verhandl. Geol. Reichsanst.* 1871, p. 165; 1872, p. 54; 1873, p. 288. In these memoirs the student will find much interesting speculation regarding the zoological distribution and organic progress and vicissitudes of climate in Europe during the Jurassic period. In the volume of the *Jahrbuch* here quoted (p. 452), there is a copious bibliography of Jurassic memoirs referring to the Eastern Alps.

[2] For British Jurassic rocks the student's attention may be specially called to Phillips' *Geology of Oxford and the Thames Valley;* Blake and Hudleston's *Yorkshire Lias;* Memoirs published by the Palæontographical Society, particularly Morris & Lycett's *Mollusca from Great Oolite;* Davidson's *Tertiary, Oolitic, and Liassic Brachiopoda;* Wright's *Oolitic Echinodermata,* and *Lias Ammonites;* Owen's *Mesozoic Reptiles; Mesozoic Mammals; Wealden and Purbeck Reptiles;* Memoirs by Mr. Sharpe and Mr. Hudleston (*Q. J. Geol. Soc.* and *Geol. Mag.* 1880–81), Mr. Judd's *Geology of Rutland* in *Mem. Geol. Surv.*, and other memoirs cited below. See also Oppel's *Juraformation Englands, Frankreichs und Deutschlands*, 1856; Quenstedt's *Der Jura*, 1858.

passed into universal use, and though some of them are uncouth English provincial names, they are as familiar to the geologists of other countries as to those of England.

The Jurassic formations stretch across England in a varying band from the mouth of the Tees to the coast of Dorsetshire. They consist of

FIG. 382.—MARSUPIALS FROM THE PURBECK BEDS.
a, Jaw of Plagiaulax minor (Falconer) ([illegible]); *b*, same (nat. size); *c*, molar ([illegible]); *d*, Triacanthodon serrula (Owen) (nat. size).

harder sandstones and limestones interstratified with softer clays and shales. Hence they give rise to a characteristic type of scenery,—the more durable beds standing out as long ridges, sometimes even with low cliffs, while the clays underlie the level spaces between. Arranged in descending order, the following subdivisions of the English Jurassic system are recognized:

			Maximum thicknesses. Feet.
Upper or Portland Oolites.	Purbeckian	Upper fresh-water beds; Middle marine beds; Lower fresh-water beds	360
	Portlandian	Portland Stone	70
		Portland Sands	150
	Kimmeridgian	Kimmeridge Clay	600
Middle or Oxford Oolites.	Corallian	Coral Rag and Calcareous Grit	250
	Oxfordian	Oxford Clay and Kellaways Rock	600
Lower or Bath Oolites.	Great Oolite	Cornbrash	40
		Bradford Clay and Forest Marble (in Dorsetshire 450 ft.)	30
		Great or Bath Oolite with Stonesfield Slate (part of Northampton Sand)	130
	Fuller's Earth.	Fuller's Earth	150
	Inferior Oolite.	Cheltenham beds	270
		Lower part of Northampton Sands, "Dogger" of Yorkshire	160
Lias.	Upper Lias (Midford Sands)		400
	Marlstone		200
	Lower Lias		900

Although these names appear in tabular order as expressive of what is the predominant or normal succession of the beds, considerable differences occur when the rocks are traced across the country. Thus the Forest Marble attains a thickness of 450 feet in Dorsetshire, but dwindles down to only 15 feet at Blenheim Park. The Inferior Oolite consists of marine limestones and shales in Gloucestershire, but chiefly of massive

estuarine sandstones and shales in Yorkshire. These differences help to bring before us some of the geographical features of the British area during the Jurassic period.

The Lias consists of three formations, well marked by physical and palæontological characters. In the Lower member numerous thin blue and brown limestones with partings of dark shale are surmounted by similar shales with occasional nodular limestone bands. The Middle Lias consists of argillaceous limestones (marlstones) with micaceous sands and clays. In its Yorkshire development this subdivision is remarkable for containing a bed of earthy carbonate of iron 15 to 20 feet thick, which has been extensively worked in the Cleveland district. The Upper division is composed of clays and shales with nodules of limestone, surmounted by sandy deposits.

These three formations are further subdivided into zones according to distinctive species of Ammonites, as follows: [1]

Upper Lias.

The upper sandy beds contain—
Ammonites of the groups *Harpoceras* and *Lytoceras*. *Ammonites* (*Harpoceras*) *opalinus*, *A. radians*, *A. Thouarsensis*, *A. insignis*. *Ammonites* (*Lytoceras*) *jurensis*, *A. hircinus* = *Jurensis* bed of Oppel (Würtemberg).
The lower clays contain—
Ammonites (*Harpoceras*) *bifrons*, *A. serpentinus*, and numbers of the group *Stephanoceras*, as *Ammonites* (*Stephanoceras*) *communis*, *A.* (*S.*) *anguinus*, *A.* (*S.*) *fibulatus* = Posidonomya bed of Oppel (Würtemberg).

Middle Lias.	5.	Zone of *Ammonites*	(*Amaltheus*) *spinatus*	= Spinatus-bed	of Oppel (Würtemberg).
	4.	"	" *margaritatus*	= Margaritatus-bed	"
	3.	"	(*Ægoceras*) *Henleyi*	= Davæi-bed	"
	2.	"	(*Amaltheus*) *Ibex*	= Ibex-bed	"
	1.	"	(*Ægoceras*) *Jamesoni*	= Jamesoni-bed	"
Lower Lias.	7.	Zone of *Ammonites*	(*Arietites*) *raricostatus*	= Raricostatus-bed	"
	6.	"	(*Amaltheus*) *oxynotus*	= Oxynotus-bed	"
	5.	"	(*Arietites*) *obtusus*	= Obtusus-bed	"
	4.	"	" *Turneri*	= Tuberculatus-bed	"
	3.	"	" *Bucklandi*	= Bucklandi-bed	"
	2.	"	(*Ægoceras*) *angulatus*	= Angulatus-bed	"
	1.	"	" *planorbis*	= Planorbis-bed	"

resting conformably on *Avicula contorta* beds.

The organic remains of the Lias comprise leaves and other remains of cycads (*Palæozamia*), conifers (*Pinites*, *Cupressus*, *Peuce*), ferns (*Otopteris*, *Alethopteris*, &c.), and reeds (*Equisetites*). These fossils serve to indicate the general character of the flora, which seems now to have been mainly cycadaceous and coniferous, and to have presented a great contrast to the lycopodiaceous vegetation of Palæozoic times. The occurrence of land-plants dispersedly throughout the English Lias shows also that the strata, though chiefly marine, were deposited within such short distance from shore, as to receive from time to time leaves, seeds, fruits, twigs, and stems from the land. Further evidence in the same direction is supplied by the numerous insect remains, which have been obtained principally from the Lower Lias. These were, no doubt, blown off the land and fell into shallow water, where they were preserved in the silt on the bottom. The *Neuroptera* are numerous, and include several species of *Libellula*.

[1] See the masterly monograph on Liassic Ammonites by Dr Wright in *Palæontograph. Soc. Memoirs.*

The coleopterous forms comprise a number of herbivorous and lignivorous beetles (*Elater*, *Carabus*, &c.). There were likewise representatives of the orthopterous, hemipterous, and dipterous orders. These relics of insect-life are so abundant in some of the calcareous bands that

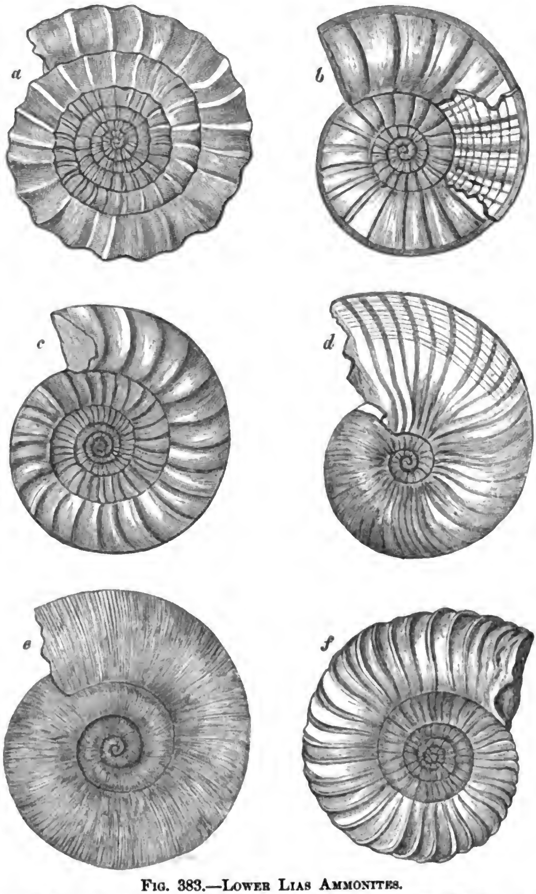

FIG. 383.—LOWER LIAS AMMONITES.

a, Ammonites (Arietites) raricostatus (Zeit.) (3/4); *b*, A. (A.) obtusus (Sby.)(1/3); *c*, A. (A.) Bucklandi (Sby.) (1/8); *d*, A. (Amaltheus) oxynotus (Quenst.) (2/3); *e*, A. (Ægoceras) planorbis (Sby.); *f*, A. (Æ.) angulatus (Schloth.) (1/2).

the latter are known as insect-beds.[1] With them are associated remains of terrestrial plants, cyprids, and molluscs, sometimes marine, sometimes

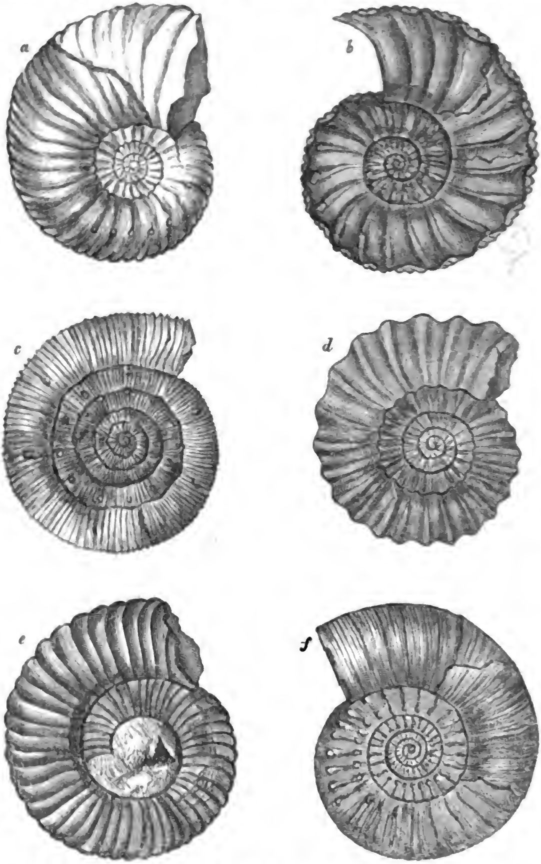

FIG. 384.—MIDDLE LIAS AMMONITES.

a, Ammonites (Amaltheus) margaritatus (Mont.) (½); *b*, A. (A.) spinatus (Brug.) (½); *c*, A. (Ægoceras) Davæi (Sby.) (½); *d*, A. (Æ.) capricornus (Schloth.) (½); *e*, A. (Æ.) Jamesoni (Sby.) (½); *f*, A. (Æ.) brevispina (Sby.) (½).

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[1] Brodie, *Proc. Geol. Soc.* 1846, p. 14; *Q. J. Geol. Soc.* v. 31, *History of Fossil Insects*, 1846.

apparently brackish-water. The marine life of the period has been abundantly preserved, so far at least as regards the comparatively shallow and juxta-littoral waters in which the Liassic strata were accumulated.[1] Corals, though on the whole scarce (67 species are known), abound on some horizons (*Astrocœnia*, *Thecosmilia*, *Isastræa*, *Montlivaltia*, *Septastræa*, &c.). The crinoids (15 species) were represented by thick growths of *Extracrinus* and *Pentacrinus*. There were brittle-stars, star-fishes, and sea-urchins (*Ophioglypha*, *Uraster*, *Luidia*, *Hemipedina*, *Cidaris*, *Acrosalenia*)—all generically distinct from those of the Palæozoic periods. Among the crustacea, the more frequent known genera are *Eryon*, *Glyphæa*,

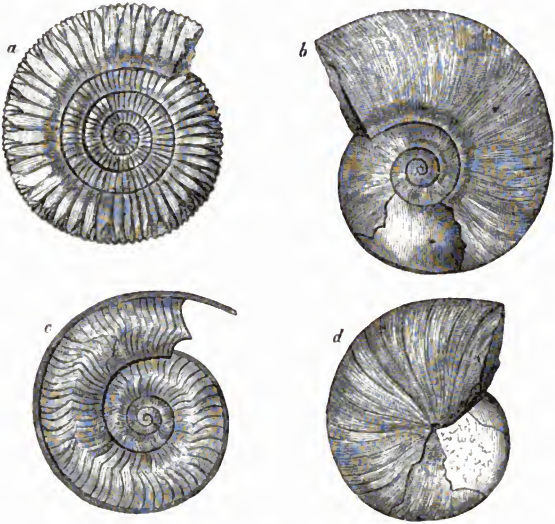

FIG. 385.—UPPER LIAS AMMONITES.

a, Ammonites (Stephanoceras) communis (Sby.) ($\frac{1}{3}$); *b*, A. (Lytoceras) jurensis (Zieten) ($\frac{1}{12}$); *c*, A. (Harpoceras) serpentinus (Rein) ($\frac{1}{4}$); *d*, A. (Phylloceras) heterophyllus (Sby.) ($\frac{1}{6}$).

and *Eryma*. The brachiopods are chiefly *Rhynchonella* (19 species), *Waldheimia* (12), *Spiriferina* (8), and *Thecidium* (16). *Spiriferina* is the last of the Spirifers, and with it are associated the last forms of *Leptæna*, of which five Liassic species are known from English localities (Fig. 369). Of the lamellibranchs, a few of the most characteristic genera are *Pecten* (25 species), *Lima* (23), *Avicula* (21), *Mytilus* (18), *Cardinia* (16), *Leda* (15), *Cypricardia* (12), *Astarte* (14), *Gryphæa*, *Pleuromya*, *Hippopodium*, and *Pholadomya*. Gasteropods, though usually rare in such muddy strata as

[1] See R. Tate, *Census of Lias Marine Invertebrata*, *Geol. Mag.* viii. p. 4.

the greater part of the Lias, occasionally occur, but most frequently in the calcareous zones. The chief genera are *Cerithium* (40 species), *Turbo* (31), *Trochus* (27), *Tectaria* (*Eucyclus*) (22), *Pleurotomaria* (23), and *Chemnitzia* (19). The cephalopods, however, are the most abundant and characteristic shells of the Lias; the family of the ammonites numbers upwards of 130 species. Many of these are the same as those that have been found in the Jurassic series of Germany, and they occupy on the whole the same relative horizons, so that over central and western Europe it has been possible to group the Lias into the various zones given in the table (p. 786). The genus *Nautilus* is represented by nine or more species. The dibranchiate cephalopods are represented by about 60 species of the genus *Belemnites*.

From the English Lias many species of fishes have been obtained. Some of these are placoids, known only by their teeth (*Acrodus*, *Ceratodus*), others only by their spines (*Nemacanthus*), and some by both teeth and spines (*Hybodus*). The ganoids are frequently found entire, the genera *Dapedius*, *Pholidophorus*, *Æchmodus*, *Lepidotus*, *Pachycormus*, and *Leptolepis* being among the most frequent. But undoubtedly the most remarkable palæontological feature in this group of strata is the number and variety of its reptilian remains. The genera *Ichthyosaurus*, *Plesiosaurus*, *Dimorphodon*, *Megalosaurus*, *Teleosaurus*, and *Steneosaurus* have been recovered, in some cases the entire skeleton having been found with almost every bone still in place.

The Lias extends continuously across England from the mouth of the Tees to the coast of Dorsetshire. It likewise crosses into South Wales. An interesting patch occurs far removed from the main mass of the formation, lying unconformably on Triassic beds at Carlisle. A considerable development of the Lias stretches across the island of Skye and adjoining tracts of the west of Scotland, where the shore-line of the period is partly traceable. In the north of Ireland also the characteristic shales appear in several places from under the Chalk escarpment.

The Lower or Bath Oolites lie conformably upon the top of the Lias, with which they are connected by a general similarity of organic remains, and by about 40 species which pass up into them from the Upper Lias. They consist in the south-west and centre of England of shelly marine limestones, with clays and sandstones, but, traced northwards into Northampton, Rutland, and Lincolnshire, they pass into a series of strata indicative of deposit in the estuary of some river descending from the north, for, instead of the abundant cephalopods of the truly marine and typical series, we meet with fresh-water genera such as *Cyrena* and *Unio*, marine forms such as *Ostrea* and *Modiola*, thin seams of lignite, thick and valuable deposits of ironstone, and remains of terrestrial plants. These indications of the proximity of land become still more marked in Yorkshire, where the strata (800 feet thick) consist chiefly of sandstones, shales with seams of ironstone and coal, and occasional horizons containing marine shells. It is deserving of notice that the Cornbrash, which forms the top of the Lower Oolite in the typical Gloucestershire district, occurs likewise in the same position in Yorkshire. Though rarely more than 8 feet thick, it runs across the country from Devonshire to Yorkshire. Thus a distinctly defined series of beds of an estuarine character is in the north homotaxially representative of the marine formations of the south-west. At the close of the

Lower Oolitic period the estuary of the northern tract was submerged, and a continuous sea-floor, that of the Cornbrash, stretched across England.

The Inferior Oolite attains its maximum development in the neighbourhood of Cheltenham, where it has a thickness of 264 feet, and consists of calcareous freestone and grit. It presents a tolerably copious suite of invertebrate remains, which resemble generically those of the Lias. The predominance of *Rhynchonella* and *Terebratula* over the rest of the brachiopods becomes still more marked. *Gryphæa*, *Lima*, *Pecten*, *Cardium*, *Myacites*, *Mytilus*, *Pholadomya*, *Trigonia* are frequent shells, while ammonites and belemnites also occur, though much more sparingly than in the Lias below, and in some of the later subdivisions of the Oolitic

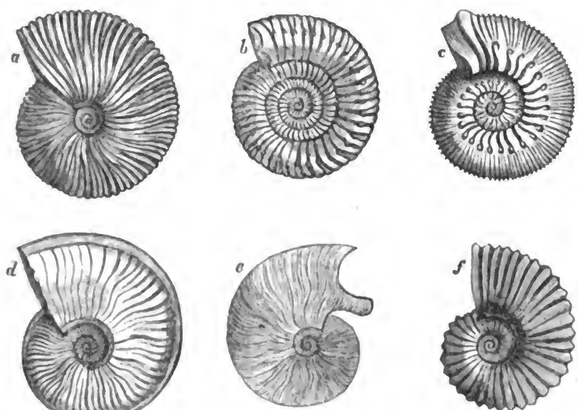

FIG. 386.—LOWER OOLITE AMMONITES.

a, Ammonites (Stephanoceras) macrocephalus (Schloth.) ($\frac{1}{3}$); *b*, A. (Cosmoceras) Parkinsoni (Sby.) ($\frac{1}{3}$); *c*, A. (Stephanoceras) Humphriesianus (Sby.) ($\frac{1}{3}$); *d*, A. (Harpoceras) Murchisonæ (Sby.) ($\frac{1}{3}$); *e*, A. (Harpoceras) opalinus (Rein) ($\frac{1}{2}$); *f*, A. (Lytoceras) torulosus (Zeit.) ($\frac{1}{3}$).

series. Palæontologically the Inferior Oolite has been subdivided into the following zones in descending order [1]:

Zone of *Ammonites* (*Cosmoceras*) *Parkinsoni*.
" " (*Stephanoceras*) *Humphriesianus*.
" " (*Harpoceras*) *Sowerbyi*.
" " (*Harpoceras*) *Murchisonæ*.

Its component strata are subject to great variations in thickness and lithological character. The thick marine series of Cheltenham is reduced in a distance of 30 or 40 miles to a thickness of a few inches. The limestones pass into sandy strata, so that in Northamptonshire the whole of

[1] On the Ammonites of these zones, see S. S. Buckman, *Q. J. Geol. Soc.* 1881. p. 588.

the formations between the Upper Lias Clay and the top of the Great Oolite consist of sands with beds of ironstone, known as the Northampton Sand. The higher portions of the sandy series contain estuarine shells (*Cyrena*) and remains of terrestrial plants. These strata swell out into a great thickness in Yorkshire, where they form the lower series of sandstones, shales, and coals. A tolerably abundant fossil flora has been obtained from these Yorkshire beds. With the exception of a few littoral fucoids all the plants are of terrestrial forms. They comprise about 60 species of ferns, among which the genera *Pecopteris*, *Sphenopteris*, *Phlebopteris*, and *Tæniopteris* are characteristic. Next in abundance come the cycads, of which more than 20 species are known (*Otozamites*, *Zamites*, *Pterophyllum*, *Cycadites*). Coniferous remains are not infrequent in the form of stems or fragments of wood, as well as in occasional twigs with attached leaves (*Araucarites*, *Brachyphyllum*, *Thuyites*, *Peuce*, *Walchia*, *Cryptomerites*, *Taxites*).

The Fuller's Earth is an argillaceous deposit which in the neighbourhood of Bath attains a maximum depth of nearly 150 feet, but dies out in Oxfordshire and is absent in the eastern and north-eastern counties. Among its more abundant fossils are *Goniomya angulifera*, *Ostrea acuminata*, *Rhynchonella concinna*, *R. varians*; but most of its fossils occur also in the Inferior Oolite.

The Great Oolite consists, in Gloucestershire and Oxfordshire, of three groups of strata: (*a*) lower group of thin-bedded limestones with sands, known as the Stonesfield Slate; (*b*) middle group of shelly and yellow or cream-coloured, often oolitic limestones, with partings of marl or clay—the Great Oolite; (*c*) upper group of clays and shelly limestones, including the Bradford Clay, Forest Marble, and Cornbrash. These subdivisions, however, cease to be recognizable as the beds are traced eastward. The Bradford Clay of the upper group soon disappears, and the Forest Marble, so thick in Dorsetshire, thins away in the north and east of Oxfordshire, the horizon of the group being perhaps represented in Lincolnshire by the "Great Oolite Clays" of that district. The Cornbrash, however, is remarkably persistent, retaining on the whole its lithological and palæontological characters from the south-west of England nearly as far as the Humber. The limestones of the middle group are less persistent, though they can be recognized as far as the middle of Lincolnshire. The lower group, including the Stonesfield Slate, passes into the upper part of the Northampton Sand and the "Upper Estuarian series." (See Mr. Judd's *Geology of Rutland*.)

The fossils of the Stonesfield Slate are varied and of high geological interest. Among them are about a dozen species of ferns, the genera *Pecopteris*, *Sphenopteris*, and *Tæniopteris* being still the prevalent forms. The cycads are chiefly species of *Palæozamia*, and the conifers of *Thuyites*. With these drifted fragments of a terrestrial vegetation there occur remains of beetles, dragon-flies, and other insects which had been blown or washed off the land. The waters were tenanted by a few brachiopods (*Rhynchonella* and *Terebratula*), by lamellibranchs (*Gervillia*, *Lima*, *Ostrea*, *Pecten*, *Astarte*, *Modiola*, *Trigonia*, &c.), by gasteropods (*Natica*, *Nerita*, *Patella*, *Trochus*, &c.), by a few ammonites and belemnites, and by placoid and ganoid fishes, of which about 50 species are known. The reptiles comprise representatives of turtles, with species of *Ichthyosaurus* and *Plesiosaurus*, *Ceteosaurus*, *Teleosaurus*, *Megalosaurus*, and *Rhamphorhynchus*

But the most important organic relics from this geological horizon are the marsupial mammalia already referred to.

The fauna of the Great Oolite includes a number of corals (*Isastræa*, *Cyathophora*, *Thamnastræa*), echinoderms, particularly of the genera *Acrosalenia*, *Clypeus*, *Echinobrissus*, and *Pseudodiadema*; numerous polyzoa (*Diastopora*, &c.), brachiopods of the genera *Rhynchonella* (*R. concinna*, *R. obsoleta*), and *Terebratula* (*T. digona*, *T. globata*, *T. maxillata*); lamellibranchs, particularly species of *Gervillia*, *Lima*, *Ostrea*, *Pecten*, *Arca*, *Astarte*, *Cardium*, *Ceromya*, *Cypricardia*, *Myacites*, *Pholadomya*, *Tancredia*; gasteropods of the genera *Actæonina*, *Nerinæa*, *Nerita*, *Buccinum*, *Murex*, *Fusus*, *Patella*, &c., and cephalopods, which, however, are comparatively rare. Some of the same genera of fishes occur as in the Inferior Oolite, and a number of the same genera of reptiles. The Bradford Clay of Wiltshire has long been well known for its pear-encrinites (*Apiocrinites rotundus*), which are found at the bottom of the clay with their base attached to the top of the Great Oolite limestone.

The Cornbrash is traceable by some species peculiar to or specially abundant in it, as *Echinobrissus clunicularis*, *E. orbicularis*, *Holectypus*

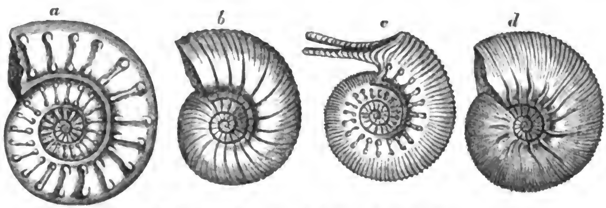

FIG. 387.—MIDDLE JURASSIC AMMONITES.
a, Ammonites (Aspidoceras) perarmatus (Sby.) (½); *b*, A. (Amaltheus) Lamberti (Sby.); *c*, A. (Cosmoceras) Jason (Zeit.) (⅓); *d*, A. (Cosmoceras) calloviensis (Sby.) (½).

depressus, *Terebratula obovata*, *T. lagenalis*, *Avicula echinata*, *Gervillia aviculoides*, *Ammonites macrocephalus* (*Herveyi*).

The MIDDLE or OXFORD OOLITES are composed of two distinct groups: (1) the Oxfordian, and (2) the Corallian.

(1.) Oxfordian, divisible into two sections: (*a*) a lower zone of calcareous abundantly fossiliferous sandstone, known, from a place in Wiltshire, as the Kellaways Rock (Callovian). This zone, after dying out in the midland counties, reappears in Lincolnshire and attains a thickness of 30 feet on the Yorkshire coast. It contains about 150 species of fossils, of which nearly a half are found in lower parts of the Jurassic series, and about the same number pass upward into higher zones. Among its characteristic forms are *Ammonites calloviensis*, *A. gowerianus*, *A. modiolaris*, *A. macrocephalus*, *Belemnites Oweni*, *Avicula inæquivalvis*, *Gryphæa bilobata*; (*b*) Oxford Clay—so called from the name of the county through which it passes in its course from the coast of Dorsetshire to that of Yorkshire—consists mainly of layers of stiff blue and brown clay, sometimes attaining a thickness of 600 feet. From the nature of its material and the conditions of its deposit, this rock is defi-

cient in some forms of life which were no doubt abundant in neighbouring areas of clearer water. Thus there are hardly any corals, and few echinoderms, polyzoa, or brachiopods. Some lamellibranchs are abundant, particularly *Gryphæa* and *Ostrea* (both forming sometimes wide oyster-beds), *Lima*, *Avicula*, *Pecten*, *Astarte*, *Trigonia* (*clavellata*), *Nucula* (*N. nuda*, *N. Phillipsii*)—the whole having a great similarity to the assemblages in the Lower Oolite formations. The gasteropods are not so numerous as in the calcareous beds below, but belong mostly to the same genera. The ammonites, especially of the *Ornatus* and *Armatus* groups, are plentiful,—*A. Duncani*, *A. Elizabethæ* (*Jason*), *A. Lamberti*, and *A. oculatus*, *A. ornatus*, *A. athleta*, being characteristic. The belemnites, which also are frequent, include *B. hastatus* (found all the way from Dorsetshire to Yorkshire), also *B. puzosianus*. The fishes include the genera *Asteracanthus*, *Hybodus*, *Ischyodus* (*Egertoni*), and *Lepidotus*. The reptilian genera *Ichthyosaurus*, *Megalosaurus*, *Plesiosaurus* (4 species), *Steneosaurus*, *Pliosaurus*, and *Rhamphorhynchus* have been noted.

(2.) Corallian, traceable with local modifications from the coast of Dorset to Yorkshire. The name of this group is derived from the numerous corals which it contains. According to the recent exhaustive researches of Messrs. Blake and Hudleston,[1] this group when complete consists of the following subdivisions:

6. Supra-Corallian beds—clays and grits, including the Upper Calcareous Grit of Yorkshire, and the Sandsfoot clays and grits.
5. Coral Rag, a rubbly limestone composed mainly of masses of coral.
4. Coralline Oolite, a massive limestone in Yorkshire, but dying out southwards and reappearing in the form of marl and thin limestone.
3. Middle Calcareous Grit, probably peculiar to Yorkshire.
2. Lower or Hambleton Oolite, not certainly recognized out of Yorkshire.
1. Lower Calcareous Grit.

The corals are found in masses in their positions of growth, forming true massive coral-reefs in Yorkshire (*Thamnastræa*, *Isastræa*, *Thecosmilia*, *Rhabdophyllia* [Fig. 365]). Numerous sea-urchins occur in many of the beds, particularly *Cidaris florigemma* (Fig. 367), also *Pygurus*, *Pygaster*, *Hemicidaris*, &c. Brachiopods are comparatively infrequent. The lamellibranchs are still largely represented by *Avicula*, *Lima*, *Ostrea*, *Pecten*, and *Gryphæa* (*Ostrea gregarea* and *Gryphæa dilatata* being specially numerous). Among the Ammonites are *A. catena*, *A. cordatus*, *A. ingens*, *A. perarmatus*, and *A. plicatilis*.

The Upper or Portland Oolites bring before us the records of the closing epochs of the long Jurassic period in England. They are divisible into three groups: (1) Kimmeridgian, at the base; (2) Portlandian, and (3) Purbeckian.

(1.) Kimmeridgian, so named from the clay at the base of the Upper Oolites, well developed at Kimmeridge, on the coast of Devonshire, whence it is traceable continuously, save where covered by the Chalk, into Yorkshire. According to Mr. J. F. Blake it may be subdivided into two sections:

(*b.*) Upper Kimmeridgian, consisting of paper-shales, bituminous shales, cement stone, and clays, characterized by a comparative paucity of forms but an infinity of individuals; perhaps 650 feet thick in Dorsetshire, but

[1] *On the Corallian Rocks of England.* *Q. J. Geol. Soc.* xxxiii. p. 260.

thinning away or disappearing in the inland counties. This zone is fairly comparable with the "Virgulian group" of foreign authors.

(*a*.) Lower Kimmeridgian, blue or sandy clay with calcareous "doggers," representing the "Astartian group" of foreign geologists. This is the great repository of the fossils of this group.[1]

Among the more common fossils are numerous foraminifera (*Pulvulina pulchella*, *Robulina Münsteri*), also *Serpula tetragona*, *Discina latissima*, *Exogyra virgula* (Fig. 373), *E. nana*, *Thracia depressa*, *Corbula Deshayesia*, *Cardium striatulum* (Fig. 373), *Belemnites nitidus*, *Ammonites biplex*, *A. decipiens*, *A. Berryeri*, *A. serratus*. Numerous remains of fishes have been obtained, also reptiles of the genera *Ischyosaurus*, *Megalosaurus*, *Ceteosaurus*, *Plesiosaurus* (12 species), *Pliosaurus* (5), *Ichthyosaurus* (9), *Teleosaurus*, *Steneosaurus*, *Dakosaurus*, and *Goniopholis*.

(2.) **Portlandian**, so named from the Isle of Portland, where it is typically developed. This group, resting directly on the Kimmeridge clay, consists of two divisions, the Portland Sand and Portland Stone. At Portland, according to Mr. J. F. Blake, it presents the following succession of beds in descending order :[2]

Portland Stone.	Shell limestone (Roach), containing *Cerithium Portlandicum* (very abundant), *Sowerbya Dukei*, *Buccinum naticoides*.
	"Whit bed" — Calcareous Freestone, the well-known Portland stone (*Ammonites giganteus*).
	"Curf," another calcareous building stone (*Ostrea solitaria*).
	"Base-bed," a building stone like the whit bed, but containing irregular bands of flint.
	Limestone, "Trigonia bed" (*Trigonia gibbosa* (Fig. 373), *Perna mytiloides*).
	Bed (3 feet) consisting of solid flint in the upper and rubbly limestone in the lower part.
	Band (6 feet) containing numerous flints (*Serpula gordialis*, *Ostrea multiformis*).
	Thick series of layers of flints irregularly spaced (*Ammonites boloniensis*, *Trigonia gibbosa*, *T. incurva*).
	Shell bed abounding in small oysters and serpulæ (*Ammonites pseudogigas*, *A. triplex*, *Pleurotomaria rugata*, *P. Rozeti*, *Cardium dissimile* (Fig. 373), *Trigonia gibbosa*, *T. incurva*, *Pleuromya tellina*).
Portland Sand.	Stiff blue marl without fossils (12 to 14 feet).
	Liver-coloured marl and sand with nodules and bands of cement stone—26 feet (*Mytilus autissiodorensis*, *Pecten solidus*, *Cyprina implicata*, *Ammonites biplex*, &c.).
	Oyster bed (7 feet) composed of *Exogyra bruntrutana*.
	Yellow sandy beds—10 feet (*Cyprina implicata*, *Arca*).
	Sandy marl (at least 30 feet) passing down into Kimmeridge clay (*Ammonites biplex*, *Lima boloniensis*, *Pecten Morini*, *Avicula octavia*, *Trigonia incurva*, *T. muricata*, *T. Pellati*, *Rhynchonella Portlandica*, *Discina Humphriesiana*).

Among Portlandian fossils a single species of coral (*Isastræa oblonga*) occurs; echinoderms are scarce (*Acrosalenia Königi*, &c.), there are also few brachiopods. The most abundant fossils are lamellibranchs, the best represented genera being, *Trigonia*, *Astarte*, *Mytilus*, *Pecten*, *Lima*, *Perna*, *Ostrea*, *Cyprina*, *Lucina*, *Cardium*, *Pleuromya*. Eight species of Ammonite occur (*A. giganteus*, *pseudogigas*, *boloniensis*, *triplicatus*, *biplex*, *pectinatus*, *Bleicheri* (?), *Boisdini*). Fish are represented by two genera (*Chimæra* and *Pycnodus*), and some of the older Jurassic saurian genera

[1] J. F. Blake *On the Kimmeridge Clay of England*. *Q. J. Geol. Soc.* xxxi.
[2] *Q. J. Geol. Soc.* xxxvi. p. 189.

(*Steneosaurus*, *Celeosaurus*) still appear, together with the crocodile *Goniopholis*.[1]

(3.) Purbeckian.—This group, so named from the Isle of Purbeck, where best developed, is usually connected with the foregoing formations as the highest zone of the Jurassic series of England. But it is certainly separated from the rest of that series by many peculiarities, which show that it was accumulated at a time when the physical geography and the animal and vegetable life of the region were undergoing a remarkable change. The Portland beds were gently upraised and even somewhat denuded before the lowest Purbeckian strata were deposited. Hence a considerable stratigraphical and palæontological break is to be remarked at this line. The sea-floor was converted partly into land, partly into shallow estuaries. The characteristic marine fauna of the Jurassic seas nearly disappeared from the area, its place being taken by fresh-water and brackish-water forms.

The Purbeckian beds have been divided into three sections. Of these the lowest consists of fresh-water limestones and clays, with layers of ancient soil ("dirt beds") containing stumps of the trees which grew in them; the middle comprises about 130 feet of strata with marine fossils, while the highest shows a return of fresh-water conditions. Among the indications of the presence of the sea is an oyster-bed (*Ostrea distorta*) 12 feet thick, with *Pecten*, *Modiola*, *Avicula*, *Thracia*, &c. The fresh-water bands contain still living genera of lacustrine and fluviatile shells (*Paludina*, *Limnæa*, *Planorbis*, *Physa*, *Valvata*, *Unio*, and *Cyclas*). Numerous fishes, both placoid and ganoid, haunted these Purbeck waters. Many insects, blown off from the adjacent land, sank and were entombed and preserved in the calcareous mud. These include coleopterous, orthopterous, hemipterous, neuropterous, and dipterous forms (Fig. 376). Remains of several reptiles, chiefly chelonian, but including the old Jurassic crocodile *Goniopholis*, have also been discovered. The most remarkable organisms of this group of strata are the mammalian forms already noticed (p. 782). It is deserving of note that these remains occur, almost wholly as lower jaws, in a stratum about 5 inches thick lying near the base of the Middle Purbeck group, these being the portions of the skeleton that would be most likely first to drop out of floating and decomposing carcases.

France, &c.—The Jurassic system is here symmetrically developed in the form of two great connected rings. The southern ring encloses the crystalline axis of the centre and south; the northern and larger ring encircles the Cretaceous and Tertiary basin and opens towards the Channel, where its separated ends point across to the continuation of the same rocks in England. But the structure of the two areas is exactly opposite, for in the southern area the oldest rocks lie in the centre and the Jurassic strata dip outwards, while in the northern region the youngest formations lie in the centre and the Jurassic beds dip inward below them. Where the two rings unite in the middle of France they send a tongue down to the Bay of Biscay. On the eastern side of the country the Jurassic system is copiously developed, and extends thence eastwards through the Jura Mountains into Germany.

The subdivisions of the Jurassic system in the north and north-west of France resemble generally those established in England, but gradually

[1] J. F. Blake, *Op. cit.*

vary from the English type as they are traced to the south and east. The following table comprises the larger sections; many of these, as in England, being further subdivided into zones characterized by peculiar or specially abundant species of fossils:[1]

Purbeckien,[2] fresh and brackish water beds with *Corbula forbesiana*, *Physa wealdiana*, *Valvata helicoides*, and other Purbeck species. Found in the Jura, lying conformably on top of Portlandien, near Morteau, valley of the Doubs.

Portlandien, a well-developed group of limestones, divisible in the Côte d'Or into an upper zone with *Trigonia boloniensis* and *Pinna supra-jurensis*, and a lower zone with *Ammonites gigas*. The group extends into the Swiss Jura, northwards down the valley of the Meuse, and reappears on the coast near Boulogne-sur-Mer, where it attains a thickness of above 200 feet, and is divisible into three bands: a lower stage (*Trigonia Micheloti*, *T. barrensis*, *T. boloniensis*, *Cardium dissimile*, *Astropecten Loriolii*, *Hemicidaris purbeckensis*, &c.); a middle stage (*Cardium morinicum*, *Ostrea expansa*, *Ammonites biplex*, *Acrosalenia Königii*); and an upper stage (*Ammonites gigas*, &c.).

Kimmeridien = Kimmeridge clay, divisible into three zones as under:
- *c.* Virgulien (*Exogyra* (*Ostrea*) *virgula*).
- *b.* Ptérocérien (*Pteroceras Oceani*).
- *a.* Astartien (Calcaires à Astartes), Sequanien in part, *Ostrea deltoidea* (Fig. 373), *Astarte minima*.

Corallien. Some authors take the upper part of this group into a separate section under the name of Sequanien, largely developed in the east of France, where it consists of massive limestones sometimes 400 feet thick. In the Ardennes also this group sometimes exceeds 400 feet in thickness, and consists of limestones. The Corallien in France and Switzerland presents three zones: 1st, an upper set of fine white earthy or siliceous limestones with *Nerinæa*, *Diceras arietinum*, &c., apparently absent in England; 2nd, a middle group of coral limestones (*Thecosmilia*, *Montlivaltia*, *Isastræa*, *Thamnastræa*, &c.); 3rd, a lower echinoderm zone (*Cidaris florigemma*, *Glypticus hieroglyphicus*).

Oxfordien (including Argovien and Callovien) consists of marls, sometimes calcareous or ferruginous. The following zones in descending order have been observed in the Côte d'Or: 1. *Ammonites plicatilis*, *Pholadomya parcicostata*; 2. *Ammonites babeanus*, *Pholodomya ampla*; 3. *Ammonites biplex*, *A. canaliculatus*, *A. Henrici*, *A. eucharis*, *Trigonia clavellata*; and large sponges (*Scyphia obliqua* and other species); 4. *Ammonites cordatus*, *A. perarmatus*, *A. oculatus*; 5. Marnes Calloviennes with *Ammonites calloviensis*, *A. macrocephalus*, *A. athleta* (= Kellaways Rock). In the Boulonnais the subdivisions in descending order are: 1. Clay with *Ammonites Mantelli*; 2. Clay with *A. cordatus*; 3. Clay and marly limestone with *A. Lamberti*; 4. Clay with *A. macrocephalus*.

Bathonien or Grande Oolithe, composed in the North of France of the following lithological zones in descending order: Calcaire à Polypiers, Calcaire de Ranville, Oolithe de Caen, Calcaire de Caen, Grande Oolithe, Terre à Foulon. In this region the palæontological zones are in descending order: 1. *Terebratula lagenalis*; 2. *Rhynchonella elegantula*; 3. *Rhynchonella decorata* or *Rh. Hopkinsii*; 4. *Cardium pes-bovis*; 5. *Clypeus Plotii*; 6. *Ostrea acuminata*. In the east of the country (Côte d'Or) the following zones have been made out in descending order—1. Flags and marls, with

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[1] See a full bibliography of works on the Jurassic Rocks of N.W. France, in an excellent paper on these rocks by Mr. J. F. Blake, *Q. J. Geol. Soc.* 1881, p. 497. Consult also D'Orbigny's *Paléontographie Française—Terrains Oolitiques*," 1842–1850; D'Archiac, *Paléontologie de la France*, 1868.

[2] Mr. J. F. Blake, in the paper already cited, proposes to class the Purbeck and Portland limestone with their equivalents under the term Portlandian as the uppermost group of the Jurassic system. Below these beds he places the middle and lower Portland as the "Bolonian group," resting upon the Virgulian beds of the Kimmeridgian, and including strata lower in position than the true Portland beds, and which are not found in the south of England.

Pentacrinus Buvignieri, Heteropora conifera; 2. Beds with *Terebratula obovata, Isastræa limitata;* 3. Beds with *Terebratula cardium, Apiocrinites Parkinsoni;* 4. Thick-bedded limestones with *Rhynchonella decorata;* 5. Oolitic limestones with *Pecten laminatus;* 6. Marls with *Ostrea acuminata.*

Bajocien, or Oolithe Inférieure, well developed in the Department of Calvados, the name of the group being taken from Bayeux. In the north of France the strata are divisible into two zones, the lower characterized by *Ammonites Murchisonæ*, the upper by *A. Blagdeni*, &c. In the east of the country this group covers a large area. In the department of Saône et-Loire it contains the following subdivisions in descending order—1. Thin-bedded oolitic limestone perforated by *Lithophaga bajocensis;* 2. Ferruginous and oolitic limestone with *Collyrites ringens, Ammonites Parkinsoni, A. subradiatus, A. garantianus;* 3. Sandy marls and calcareous bands, *Terebratula Phillipsii, Rhynchonella* (numerous species), *Ammonites interruptus, A. Truellei*, &c.; 4. Coral-limestone composed of reefs of *Thamnastræa, Isastræa*, &c., with *Ammonites Sauzei, Pinna inornata, Rhynchonella costata*, &c.; 5. Reddish or white thick-bedded limestone (Calcaire à Entroques) with thin marly beds full of sponges, polyzoa, and fragments of crinoids, *Ammonites Murchisonæ, Belemnites giganteus, Pholodomya fidicula, Trigonia striata*, &c.; 6. Brown siliceous limestone with *Pecten personatus*, resting upon ferruginous sands containing *Ammonites opalinus*, which form the top of the Lias.

Toarcien (from Thouars = Upper Lias), composed of alternations of limestone and clays capable of palæontological separation into an upper series containing *Ammonites opalinus, A. thouarsensis, A. radians, A. insignis, A. variabilis, A. mucronatus;* a middle series with *A. radians, A. bifrons;* and a lower series with *A. serpentinus, A. complanatus, Rhynchonella tetrahedra.*

Liassien (= Middle Lias), composed of marls and argillaceous limestones divisible into a series of zones characterized by many of the same Ammonites as the Middle Lias of England.

Sinémurien (= Lower Lias), composed of argillaceous limestones, and marls with the normal series of Ammonite zones. *Ostrea arcuata, Belemnites brevis.*

Hettangien (Infra-Lias), marly and shelly limestones with *Ammonites planorbis*, &c., and corresponding to the Angulatus and Planorbis zones at the base of the Lias, resting conformably on the sandstones, marls, and bone-bed of the *Avicula contorta* zone or Rhætic.

One of the most interesting features of the Lias in the northern or Jura part of Switzerland is the insect beds at Schambelen in the Canton Aargau. The insects are better preserved and much more varied than in the English Lias, and include representatives of Orthoptera, Neuroptera, Coleoptera (upwards of 100 species of beetles), Hymenoptera, and Hemiptera. About half of the beetles are wood-eating kinds, so that there must have been abundant woodlands on the Swiss dry land in Liassic time.[1]

In north-western Germany the subjoined classification has been adopted:[2]

Upper or White Jura (Malm).	Purbeck group (Serpulit, Münder Mergel), forming a transition between Purbeck and Portland.
	Eimbeckhäuser Plattenkalke and zone of *Amm. giganteus*, equivalent to the English Portland.
	Kimmeridge group (Upper, with *Exogyra virgula;* Middle or *Pterocera* beds; Lower or Astartian with *Nerinæa* beds and zone of *Terebratula humeralis*[3]).
	Oxford group (Upper or Corallian, with *Cidaris florigemma;* Lower or Oxford [*Hersumer schichten*], with *Gryphæa dilatata*).

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[1] Heer, *Urwelt der Schweiz*, p. 82.

[2] Heinr. Credner, *Ober. Jura in N. W. Deutschland*, 1863. See also the works of Oppel and Quenstedt quoted on p. 784, and K. von Seebach's *Der Hannoversche Jura*, 1864. Brauns' *Unter., Mittl. und Ober. Jura*, 1869, 1871, 1874.

[3] Struckmann, *N. Jahrb.* 1881, p. 102.

Middle or Brown Jura (Dogger).	Upper	Clays with *Ammonites ornatus*.
		Shales with *A. macrocephalus*.
		Cornbrash with *Avicula echinata*, *Amm. posterus*.
		Shales with *Ostrea Knorri*, *Amm. ferrugineus*.
		Zone of *Amm. Parkinsoni*.
	Middle	Coronaten-Schichten, clays with *Belemnites giganteus*, *Amm. Humphriesianus*, *Amm. Braikenridgi*.
	Lower	Shales, sandstones, and ironstones, with *Inoceramus polyplocus*, *Amm. Murchisonæ*.
		Clays and shales with *Amm. opalinus*.
Lower or Black Jura (Lias).	Upper	Grey marls with *Ammonites jurensis*.
		Bituminous shales (Posidonien-schiefer) with *Amm. lythensis*, *A. communis*, *A. bifrons*, *Posidonia Bronni*.
	Middle	Clays with *Amm. spinatus*.
		Marls and limestones with *Amm. capricornus*, *A. Davœi*.
		Dark clays and ferruginous marls with *A. brevispina*.
	Lower	Clays with *Amm. planicosta*, *A. raricostatus*.
		Blue grey clays with *A. Bucklandi* (Arietenschichten).
		Dark clays with *A. angulatus*.
		Dark clays and sandy layers with *A. planorbis* (*psilonotus*).

In lithological character the German Lias presents many points of resemblance to that of England. Some of the shales in the upper division are so bituminous as to be workable for mineral oil. With the general succession of organisms also, so well worked out by Oppel, Quenstedt, and others, the English has been found to agree closely. The Dogger or Brown Jura represents the Lower Oolite of England and the Etage Bajocien and Bathonien of France. Its lower division consists mainly of dark clays and shales, passing up in Swabia into brown and yellow sandstones with oolitic ironstone. The central group in northern Germany differs from the corresponding beds in England, France, and southern Germany by the great preponderance of dark clays and ironstone nodules. The upper group consists essentially of clays and shales with bands of oolitic ironstone, thus presenting a great difference to the massive calcareous formation on the same platform in England and France. The Malm, or Upper (white) Jura corresponds to the Middle and Upper Oolites of England, from the Kellaways rock upwards, with the equivalent formations in France. It is upwards of 1000 feet thick, and derives its name from the white or light colour of its rocks contrasted with the dark tints of the Jurassic strata below. It consists mainly of white limestones in many varieties; other materials are dolomite and calcareous marl. Its lower (Oxford) group is essentially calcareous, with no lithological equivalent of the true Oxford clay, but it contains some of the fossils which occur in that clay, *e.g. Ammonites cordatus* and *Gryphæa dilatata*. The massive limestones with *Cidaris florigemma* are doubtless the equivalents of the Corallian. The Kimmeridge group presents at its base beds equivalent to the Astartian zone of France (*Astarte supracorallina*, *Natica globosa*, &c.), with such an abundance and variety of the gasteropod genus *Nerinea* that the beds have been named the "Nerineen-Schichten." Above these come beds with *Pteroceras Oceani*, marking the central zone of the Kimmeridge formation. Higher still lie compact and oolitic limestones with *Exogyra virgula*, representing the upper or Virgulian stage. At the top come limestones and marly clays with *Ammonites giganteus*, which indicate the Portland formation. The most important member of the German Kimmeridge series is undoubtedly the limestone long quarried for lithographic stone at Solenhofen near Munich. Its excessive

fineness of grain has enabled it to preserve in the most marvellous perfection the remains of a remarkably varied and abundant fauna both of the sea and land. Beside skeletons of fishes (*Aspidorhynchus*, *Lepidotus*, *Megalurus*), cephalopods showing casts of their soft parts, crabs with every part of the integument in place, and other denizens of the water, there lie the relics of a terrestrial fauna washed or blown into the neighbouring shallow lagoons—dragonflies with the lace-work of their wings, and other insects, the entire skeletons of Pterodactyle and Rhamphorhyncus, in one case with the wing membrane preserved, and the remains of the earliest known bird, *Archæopteryx* (see pp. 778, 781). The German Purbeck group attains an enormous development in Westphalia (1650 feet), where between limestones full of *Corbula*, *Paludina*, and *Cyclas*, pointing to fresh-water deposition, there occur beds of gypsum and rock-salt.

Alps.—The Jurassic system in the Alps is not so well developed as in other parts of Europe. The Lias is there recognizable by fossils which in their specific forms and general succession may be paralleled in a broad way with those of the same formation elsewhere. It lies conformably on the Rhætic, but between it and the overlying Jurassic groups there is a marked unconformability. At the top of the Alpine Jurassic series an important group of deposits occurs to which the name of Tithonian stage was given by Oppel.[1] Much discussion has arisen as to whether this stage should be referred to the Jurassic or Cretaceous system. The geologists of Bavaria and Austria assign it to the former, while those of France place it with the latter. According to the one view the base of the group is marked by the zone of *Ammonites* (*Oppelia*) *tenuilobatus* (*Aspidoceras acanthicum*), over which comes a mass of strata consisting sometimes of reddish well-bedded limestones so full of *Terebratula diphya* (*janitor*) as to be named the "Diphya-limestone;" sometimes of thick-bedded or massive light-coloured limestones (Stramberg limestone, from Stramberg in Moravia). The limestones are often crowded with cephalopods, of which a large number of species, many of them peculiar, have been noticed. The shales or impure shaly limestones are sometimes full of the curious cephalopod-appendages known as *Aptychus* (Aptychus-beds). Some of the more massive limestones are true coral reefs. On the other hand, it is contended by M. Hébert and other geologists of France that the position of the zone of *Amm. tenuilobatus* has been mistaken. He believes that this zone is really more ancient than the Coral-rag of the North, and that the limestones with *Terebratula diphya* and a large cephalopodous fauna are certainly Neocomian. The Diphya-limestone with its peculiar fossils appears to range from the Carpathians through the Alps and Apennines into Sicily.

North America.—So far as yet known, rocks of Jurassic age play but a subordinate part in North American geology. Perhaps some of the red strata of the Trias belong to this division, for it is difficult, owing to paucity of fossil evidence, to draw a satisfactory line between the two systems. Strata containing fossils believed to represent those of the European Jurassic series have been met with in recent years during the explorations in the western domains of the United States. They occur

[1] *Zeit. Deutsch. Geol. Ges.* xvii. (1865), 535. See also M. Neumayr, *Abhandl. Geol. Reichsanstalt.* v.; Zittel, *Palæont. Mittheil. Mus. Bayer.*; Hébert, *Bull. Soc. Géol. France*, ii. (2nd Sér.), 148; W. Benecke, *Trias und Jura in den Sudalpen*, 1866; C. Moesch, *Jura in den Alpen, Ostschweiz*, 1872. See also the *Jura-studien*, of Neumayr, already cited (p. 784).

among some of the eastern ranges of the Rocky Mountains (Colorado; Black Hills, Dakotah; Wind River Mountains; Uinta Mountains; Wahsatch range, &c.), as well as in the Sierra Nevada and other localities on the western side of the watershed. They have been recognized also far to the north beyond the great region of Azoic and Palæozoic rocks in the arctic portion of the continent. They consist of limestones and marls, which appear seldom to exceed a few hundred feet in thickness. The fossils include species of *Pentacrinus*, *Monotis*, *Trigonia*, *Lima*, *Ammonites*, and *Belemnites*. But recent discoveries by Professor Marsh of Yale College have brought to light from the upper Jurassic strata of Colorado a remarkable series of reptilian forms which have given a wholly new interest and importance to the Jurassic rocks of America. Among remains of fish (*Ceratodus*), tortoises, pterodactyls, and crocodilians, he has recognized the bones of carnivorous and herbivorous deinosaurs. One of these, the *Atlantosaurus*, has already been referred to. Other forms are *Morosaurus*, *Apatosaurus*, *Creosaurus*, and *Laosaurus*, the latter having more ostrich-like affinities. With this rich and striking reptilian fauna are associated the remains of some small marsupials (*Dryolestes priscus*, *Stylacodon gracilis*).

Asia.—In India the upper part of the enormous Gondwana system is possibly referable to the Jurassic period. In Cutch, however, a marine series of strata occurs containing a representation of the European Jurassic system from the Inferior Oolite up to the Portland inclusive. These rocks attain a thickness of 6300 feet, of which the lower half is chiefly marine and the upper mainly fresh-water. Among the zones recognized by Stoliczka were those of *Ammonites macrocephalus*, *A. anceps*, and *A. athleta* of the Kellaways (Callovian) group; *A. Lamberti*, *A. cordatus*, *A. transversarius* of the Oxford clay; *A. tenuilobatus* of the Kimmeridge.[1]

Australasia.—The existence of Jurassic rocks in Queensland and Western Australia has been demonstrated by the discovery of recognizable Jurassic species and others closely allied to known Jurassic forms.[2] Traces of the same system have been found in New Caledonia and the northern end of New Guinea. In Otago, New Zealand, the Putakaka formation of Hutton, estimated to be between 9000 and 10,000 feet thick, is referred by him to the middle or lower Jurassic period. It has yielded a few fossils (*Pholadomya*, *Astarte*, *Ammonites*).

Section III.—Cretaceous.

The next great series of geological formations is termed the Cretaceous system, from the fact that in north-western Europe one of its most important members is a thick band of white chalk (*creta*). It presents very considerable lithological and palæontological differences as it is traced over the world. In particular, the white chalk whence its name was taken is almost wholly confined to the Anglo-Parisian basin where the system was first studied. Probably no contemporaneous group of rocks presents more remarkable local

[1] Medlicott & Blanford's *Geology of India*, p. 253.
[2] Moore, *Q. J. Geol. Soc.* xxvi. 261. W. B. Clarke, *Op. cit.* xxiii. 7.

differences than the Cretaceous system of Europe. These differences are the records of an increasing diversity of geographical conditions in the history of the Continent.

§ 1. General Characters.

Rocks.—In the European area, as will be afterwards pointed out in more detail, two tolerably distinct areas of deposit can be recognized, each with its own character of sedimentary accumulations. The northern tract includes Britain, the lowlands of Central Europe southwards into Silesia, Bohemia, and round the Ardennes into the basin of the Seine. The southern region embraces the centre and south of France, the range of the Alps, and the basin of the Mediterranean eastwards into Asia. In the northern area, which appears to have been a basin in great measure shut off from free communication with the Atlantic, the deposits are largely of a littoral or shallow-water kind. The basement beds, usually sands or sandstones, sometimes conglomerates, are to a large extent glauconitic (greensand). The marked diffusion of glauconite both in the sandstones and marls is one of the distinctive characters of this series of rocks. In Saxony and Bohemia the whole Cretaceous system consists chiefly of massive sandstones, which appear to have accumulated in a gulf along the southern margin of the northern basin. Considerable bands of clay, occurring on different platforms among the European Cretaceous rocks, are often charged with fossils, sometimes so well preserved that the pearly nacre of the shell remains, in other cases encrusted or replaced by marcasite. Alternations of soft sands, clays, and shales, usually more or less glauconitic, are of frequent occurrence in the lower parts of the system (Neocomian and older Cenomanian). The calcareous strata assume sometimes the form of soft marls, which pass into glauconitic clays on the one hand and into white chalk on the other. The white chalk is a pulverulent limestone composed of fragmentary shells and foraminifera, the upper part showing layers of flints. In some places it becomes a hard dull limestone breaking with a splintery fracture. Nodular phosphate of lime occurring on different horizons is extensively worked as a source of artificial manure. Seams of coal appear in the Lower Cretaceous series of northwestern Germany, as well as beds of concretionary limonite. In the southern basin, where the conditions of deposit appear to have been more those of an open sea freely communicating with the Atlantic, the most noticeable feature is the massiveness, compactness, and persistence of the limestones, which cover a large part of Southern Europe. These rocks from their extent and organic contents indicate that during Cretaceous times the Atlantic extended across the south of Europe and north of Africa, far into the heart of Asia, and may not impossibly have been connected across the north of India with the Indian Ocean.

Life.—The Cretaceous system, both in Europe and North America, presents successive platforms on which the land vegetation of the period has been preserved, though most of the strata contain only marine organisms. This terrestrial flora possesses a great interest, for it includes the earliest known progenitors of the abundant dicotyledonous angiosperms of the present day. In the earlier part of the Cretaceous period, it appears to have closely resembled the vegetation of the previous ages, for the same genera of ferns, cycads, and conifers, which formed the Jurassic woodlands, are found in the rocks. Yet that angiosperms must have already existed is made almost certain by the sudden appearance of numerous forms of that class, at the base of the Upper Cretaceous formation in Saxony and Bohemia, whence forms of *Acer*, *Alnus*, *Credneria*, *Cunninghamites*, *Salix*, &c., have been obtained. Still more varied and abundant is the dicotyledonous flora preserved in the highest zones of the system at Aix-la-Chapelle. The number of species of plants obtained from that locality has been estimated by M. Debey at more than 400. Of

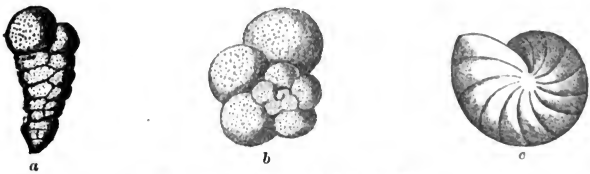


Fig. 388.—CRETACEOUS FORAMINIFERA.
a, Gaudryina pupoides (D'Orb.); *b*, Globigerina cretacea (D'Orb.); *c*, Cristellaria rotulata (D'Orb.) (all magnified).

these 70 or 80 are cryptogams, chiefly ferns (*Gleichenia*, *Lygodium*, *Asplenium*, &c.); there are numerous conifers (some akin to *Sequoia*), and three or four kinds of screw-pine (*Pandanus*). The prevalent forms which give so modern an aspect to this flora are *Proteaceæ*, many of them being referred to genera still living in Australia or at the Cape of Good Hope. There occur also species of oak, bog-myrtle, &c. These interesting fragments serve to show that the climate of Europe at the close of the Cretaceous period was doubtless greatly warmer than that which now prevails, and nourished a vegetation like that of some parts of Australia or the Cape. Further information has been afforded regarding the extension of this flora by the discovery in North Greenland of a remarkable series of fossil plants. From certain Lower Cretaceous beds of that arctic region, Heer has described 30 species of ferns, 9 cycads, and 17 conifers; while from the Upper Cretaceous rocks of Noursoak, he enumerates species of poplar, fig, sassafras, credneria, and magnolia.

In North America, also, abundant remains of a similar vegetation have been obtained from the Cretaceous rocks of the Western Terri-

tories. Upwards of 100 species of dicotyledonous angiosperms have been obtained, and of these half are found to be related to still living American trees. Among them are species of oak, willow, beech, plane, poplar, maple, hickory, fig, tulip-tree, sassafras, sequoia, together with American palms (sabal) and cycads.

The known Cretaceous fauna is tolerably extensive. Foraminifera now reached an importance as rock-builders which they had never before attained. Their remains are abundant in the white chalk of the northern European basin, and some of the hard limestones of the southern basin are mainly composed of their aggregated shells. Some of the more frequent genera are *Globigerina, Orbitolina, Nodosaria, Textilaria,* and *Rotalia* (Fig. 388). Sponges also must have swarmed on the floor of the Cretaceous seas, for their siliceous spicules are very abundant, and entire individuals are not uncommon.[1] Characteristic genera (Fig. 389) are *Ventriculites, Siphonia, Scyphia,* and *Manon.* The formation of flints has been referred to the operation of sponges. Undoubtedly these animals secreted an enormous quantity of silica from the water of the Cretaceous sea, and though the flints are certainly not due merely to their action, these amorphous lumps of silica may have been aggregated by a process of chemical elimination round dead sponges (see pp. 469, 488). Even molluscs and urchins have been completely silicified in the chalk. On the whole, corals are not abundant in Cretaceous deposits. Some of the more characteristic forms are *Trochocyathus, Cyathina, Trochosmilia, Parasmilia, Micrabacia,* and *Cyclolites.* The earliest true madrepores appear in *Actinacis.* The rugose corals so abundant among Palæozoic rocks have now almost entirely disappeared, being represented only by the little Neocomian *Holocystis.* Sea-urchins are conspicuous among the fossils of the Cretaceous system. A few of their genera are also Jurassic, while a not inconsiderable number still live in the present ocean. One of the most striking results of recent deep-sea dredging is the discovery of so many new genera of echinoids either identical with or very nearly resembling those of the Cretaceous period, and having thus an unexpectedly antique character.[2] Some of the most abundant and typical Cretaceous genera are *Ananchytes, Holaster, Toxaster, Micraster, Hemiaster, Hemipneustes, Pygurus, Echinobrissus (Nucleolites), Echinoconus (Galerites),*

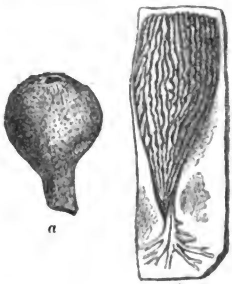


Fig. 389.—CRETACEOUS SPONGES. *a*, Siphonia pyriformis (Goldf.) (½); *b*, Ventriculites decurrens, var. tenuiplicatus (Smith) (½).

[1] See on sponge spicules papers by Mr. Sollas, *Ann. Mag. Nat. Hist.* ser. 5, vi., and a memoir by Dr. H. G. J. Hinde, *Fossil Sponge Spicules*, Munich, 1880.

[2] A. Agassiz, Report on Echinoidea, *Challenger Expedition*, vol. iii. p. 25.

Discoidea, Cyphosoma, Diadema, Salenia, Cidaris. A few crinoids have been met with of which ***Bourgueticrinus*** and ***Marsupites*** of the upper chalk are characteristic.

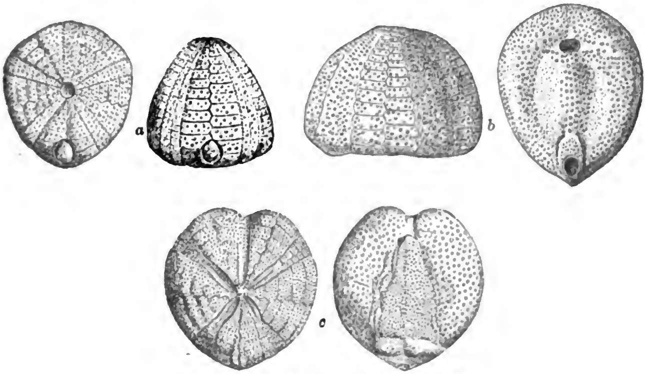


FIG. 390.—UPPER CRETACEOUS ECHINIDS.
a, Echinoconus conicus (Brey.) (Galerites albo-galerus) ([illegible]) ; *b*, Ananchytes ovatus (Leske) (½) ; *c*, Micraster cor-anguinum (Klein) (½).

Passing to the mollusca, we find the brachiopods (Fig. 391) abundantly represented by species of *Terebratula* and *Rhynchonella,* which approach in form to still living species. Other contemporaneous

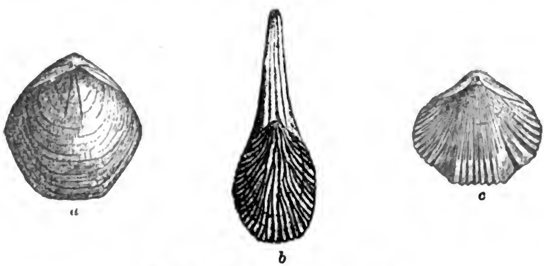


FIG. 391.—CRETACEOUS BRACHIOPODS.
a, Terebratula carnea (Sow.) ([illegible]) ; *b*, Terebrirostra lyra (Sow.) ([illegible]) ; *c*, Rhynchonella plicatilis, var. octoplicata (Sow.) ([illegible]).

genera were *Crania, Thecideum, Magas, Terebratella, Terebrirostra,* and *Terebratulina.* Among the most abundant genera of lamellibranchs are (Fig. 392) *Inoceramus, Exogyra, Ostrea, Spondylus,*

Lima, Pecten, Perna, Modiola, Lyriodon, Isocardia, Cardium, Venus. Inoceramus and *Exogyra* are specially characteristic, but still more so is the family of *Hippuritidæ* or *Rudistes.* These singular forms are entirely confined to the Cretaceous system; their most common genera (Fig. 393) being *Hippurites, Radiolites, Sphærulites, Caprina,* and *Caprotina.* Hence, according to present knowledge, the occurrence of hippurites in a limestone suffices to indicate the Cretaceous age of the rock. The most common gasteropods belong to the genera *Natica, Nerinea, Turritella, Turbo, Solarium, Trochus, Pleuro-*

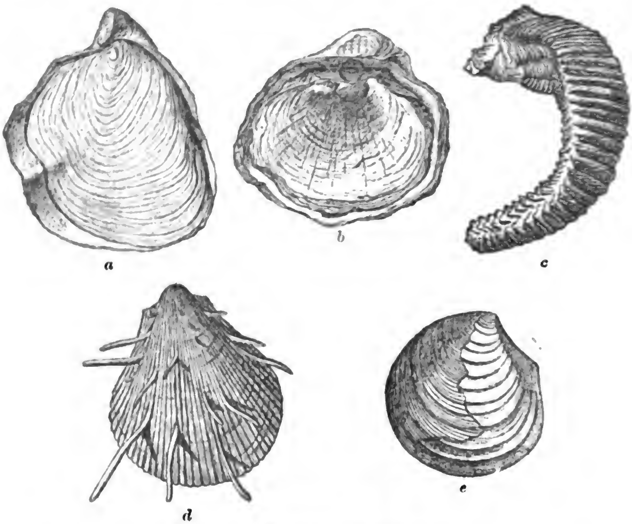
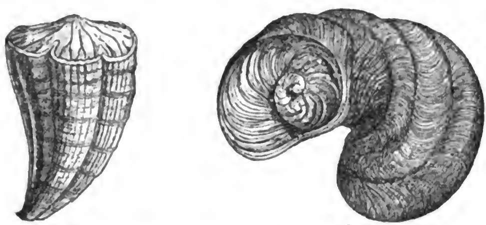


FIG. 392.—CRETACEOUS LAMELLIBRANCHS.

a, Exogyra (Ostrea) columba (Lam.)($\frac{1}{2}$); *b*, Ostrea vesicularis (Lam.) ($\frac{1}{2}$); *c*, Ostrea carinata (Lam.) ($\frac{1}{2}$); *d*, Spondylus (Lima) spinosus (Desh.) ($\frac{2}{3}$); *e*, Inoceramus Cuvieri (Sow.) (young spec.) ($\frac{1}{2}$).

tomaria, Cerithium, Rostellaria, Aporrhais, and *Fusus.* Cephalopods must have swarmed in some of the Cretaceous seas (Figs. 394, 395, 396). Their remains are abundant in the Anglo-Parisian basin and thence eastwards, but are comparatively infrequent in the southern Cretaceous area. To the geologist they have a value similar to those of the Jurassic system, as distinct species are believed to be restricted in their range to particular horizons which have by their means been identified from district to district. To the student of the history of life they have a special interest, as they include the last of the great

Mesozoic tribes of the Ammonites and Belemnites. These organisms continue abundant up to the top of the Cretaceous system and then disappear from the geological record. Never was cephalopodous life so varied as in the Cretaceous period just before its decline. Besides the forms that survived from earlier periods, but which had undergone important modifications, new types now appeared. Of these *Crioceras* (Fig. 394) was an Ammonite with the coils of the shell not contiguous. *Scaphites* and *Ancyloceras* have the last coil straightened and its end bent into a crozier-like shape (Fig. 395). *Toxoceras*, as its name implies, is merely bent into a bow-like form. *Hamites* is a long tapering shell, bent round hook-wise upon itself. In *Ptychoceras* the long tapering shell is bent once and the two parts are mutually adherent. *Turrilites* is a spirally coiled shell, and *Helicoceras* resembles it, but has the coils not in contact. *Baculites* is the simplest of all the forms, being a mere straight-chambered shell somewhat like the ancient *Orthoceras*. These forms, in numerous species, are almost



a *b*

FIG. 393.—CRETACEOUS LAMELLIBRANCHS (HIPPURITIDS).
a, Hippurites organisans (Desm.) (nat. size); *b*, Caprotina ammonia (D'Orb.) (⅓).

entirely confined to the Cretaceous system, at the summit of which they disappear. Another characteristically Cretaceous cephalopod is *Belemnitella* (Fig. 396), which occurs only in the higher parts of the system.

Vertebrate remains have been obtained in some number from the Cretaceous rocks. Fish are represented by scattered teeth, scales, or bones, sometimes by more entire skeletons. The most frequent genera are *Otodus, Lamna, Oxyrhina, Ptychodus, Hybodus, Pycnodus, Sphærodus*, and the earliest of the teleostean tribes, which include the vast majority of modern fishes—*Enchodus, Stratodus, Beryx, Syllæmus*, &c.

Reptilian life has not been so abundantly preserved in the Cretaceous as in the Jurassic system, nor are the forms so varied. In the European area the remains of Chelonians of several genera (*Chelone, Protemys, Platemys*) have been recovered. Deinosaurs are represented by the huge *Iguanodon* of the Weald (Fig. 397), and by the Jurassic *Megalosaurus* and *Ceteosaurus*, which still survived.

Lizards are represented by *Raphiosaurus, Coniosaurus, Dolichosaurus,* and *Leiodon.* The gigantic *Mosasaurus,* placed among Lacertilians by Owen, but among "pythonomorphs" by Cope, is estimated to have had a length of 75 feet, and was furnished with fin-like paddles, by which it moved through the water. True crocodiles frequented the rivers of the period, for the remains of several genera have been recognized (*Goniopholis, Pholidosaurus, Diplosaurus*). The

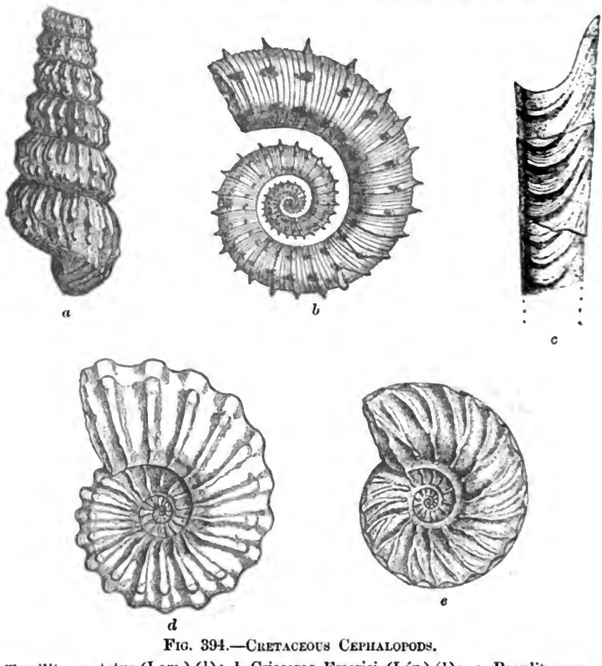


Fig. 394.—Cretaceous Cephalopods.

a, Turrilites costatus (Lam.) (½); *b*, Crioceras Emerici (Lév.) (½); *c*, Baculites anceps (Lam.) (½): *d*, Ammonites (Acanthoceras) rothomagensis (Brong.) (¼); *e*, Ammonites varians (Sow.) (⅔).

ichthyosaurs and plesiosaurs were still represented in the Cretaceous seas of Europe. The pterosaurs likewise continued to be inhabitants of the land, for the bones of several species of pterodactyle have been found. These remains are usually met with in scattered bones, only found at rare intervals and wide apart. In a few places, however, reptilian remains have been disinterred in such numbers from local deposits as to show how much more knowledge may yet be acquired

from the fortunate discovery of other similar accumulations. Thus from the so-called "Cambridge Greensand"—a bed about 1 foot thick lying at the base of the Chalk of Cambridge, and largely worked for phosphate of lime derived from coprolites and bones,

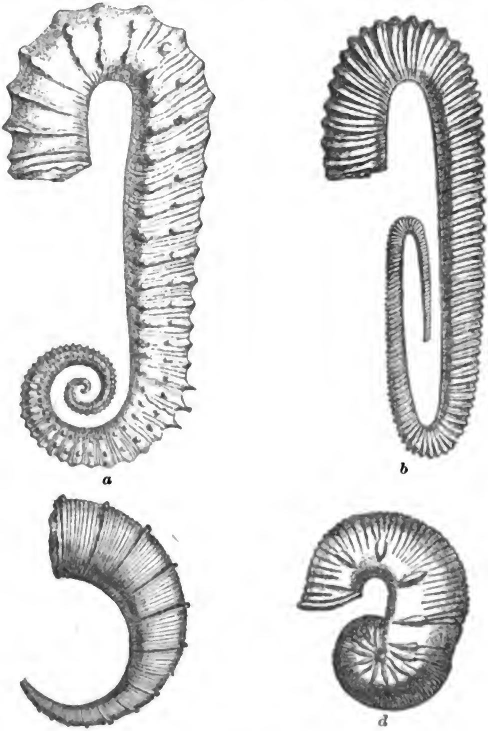


FIG. 395.—CRETACEOUS CEPHALOPODS.
a, Ancyloceras matheronianus (D'Orb.) ($\frac{1}{4}$); *b*, Hamites attenuatus (Sow.) ($\frac{1}{2}$); *c*, Toxoceras bituberculatus (D'Orb.); *d*, Scaphites æqualis (Sow.).

there have been exhumed the remains of several chelonians, the great deinosaur *Acanthopholis*, several species of *Plesiosaurus*, 5 or 6 species of *Ichthyosaurus*, 10 species of *Pterodactylus* from the size of a pigeon upwards—one of them having a spread of wing amounting to 25 feet—3 species of *Mosasaurus*, a crocodilian (*Polypty-*

chodon), and some others. From the same limited horizon also the bones of at least two species of birds have been obtained.

In recent years the most astonishing additions to our knowledge of ancient reptilian life have been made from the Cretaceous rocks of western North America, chiefly by Professors Leidy, Marsh, and Cope.[1] According to a recent enumeration made by Mr. Cope, but which is already below the truth, there were known 18 species of deinosaurs, 4 pterosaurs, 14 crocodilians, 13 sauropterygians or sea-saurians, 48 testudinates (turtles, &c.), and 50 pythonomorphs or sea-serpents. One of the most extraordinary of reptilian types was the *Discosaurus* or *Elasmosaurus*—a huge snake-like form 40 feet long, with slim arrow-shaped head on a swan-like neck rising 20 feet out of the water. This formidable sea-monster "probably

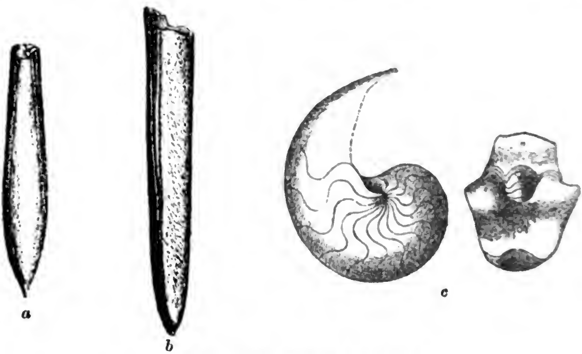


FIG. 396.—CRETACEOUS CEPHALOPODS.
a, Belemnitella plena (Blainv.) (½); *b*, Belemnitella mucronata (Schloth.) (½); *c*, Nautilus danicus (Schloth.) (½).

often swam many feet below the surface, raising the head to the distant air for a breath, then withdrawing it and exploring the depths 40 feet below without altering the position of its body. It must have wandered far from land, and that many kinds of fishes formed its food is shown by the teeth and scales found in the position of its stomach" (Cope). The real rulers of the American Cretaceous waters were the pythonomorphic saurians or sea-serpents, in which group Mr. Cope includes forms like *Mosasaurus*, of which upwards of 40 species have been discovered. Some of them attained a length of 75 feet or more. They possessed

[1] Leidy, *Smithson. Contrib.* 1865, No. 192; *Rep. U. S. Geol. and Geograph. Survey of Territories*, vol. i. (1873); Cope, *Rep. U. S. Geol. and Geograph. Survey of Territories*, vol. ii. (1875); *Amer. Naturalist*, 1878; Marsh, *Amer. Journ. Science*, numerous papers in 3rd series, vols. i.–xxii.

a remarkable elongation of form, particularly in the tail; their heads were large, flat, and conic, with eyes directed partly upwards. They swam by means of two pairs of paddles, like the flippers of the whale, and the eel-like strokes of their flattened tail. Like snakes they had four rows of formidable teeth on the roof of the mouth, which served as weapons for seizing their prey. But the most remarkable feature in these creatures was the unique arrangement for permitting them to swallow their prey entire, in the manner of snakes. Each half of the lower jaw was articulated at a point nearly midway between the ear and the chin, so as greatly to widen the space between the jaws, and the throat must, consequently, have been loose and baggy like a pelican's. The deinosaurs were likewise well represented on the shores of the American waters. Among the known forms are *Hadrosaurus*, a creature like the *Iguanodon*, and about 28 feet long; *Lælaps*, of about equal dimensions, resembled the *Megalosaurus*, having massive hind feet on which it could probably erect itself. Still more gigantic was the allied *Ornithotarsus*, which is supposed to have had a length of 35 feet. Pterosaurs have likewise been obtained characterized by an absence of teeth (*Pteranodonts*), and some of which had a spread of wing of 20 to 25 feet. Among the Chelonians one gigantic species is supposed to have measured upwards of 15 feet between the tips of the flippers.

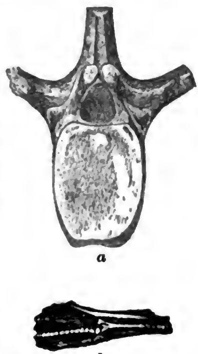


FIG. 397. — CRETACEOUS DEINOSAUR (IGUANODON). *a*, Caudal vertebra, front view ($\frac{1}{3}$); *b*, Tooth, upper jaw ($\frac{1}{3}$).

The remains of birds have been met with both in Europe and in America among Cretaceous rocks. From the Cambridge Greensand bones of at least two species, referred to the genus *Enaliornis*, have been obtained. These creatures are regarded by Professor Seeley as having osteological characters that place them with the existing natatorial birds.[1] But among the most remarkable fossil avian remains yet found are those of the *Odontornithes*, or toothed birds, from the Cretaceous beds of Kansas. Professor Marsh, who has described these interesting and wonderfully preserved forms, points out that in one of the genera,[2] named by him *Hesperornis*, the jaws were furnished with teeth implanted in a common alveolar groove, as in Ichthyosaurus; the wings were rudimentary or aborted, so that locomotion must have been entirely performed by the powerful hind limbs, with the aid of a broad, flat, beaver-like tail, which no doubt materially helped in

[1] *Q. J. Geol. Soc.* 1876, p. 496.

[2] "Odontornithes," being vol. i. of *Memoirs of Peabody Museum of Yale College*, and also vol. vii. of *Geol. Explor. 40th Parallel*.

steering the creature through the water. *Hesperornis regalis* (Fig. 398), the type species, must have measured about 6 feet from the point of the bill to the tip of the tail. The other genera, *Ichthyornis* (Fig. 399) and *Apatornis*, were distinguished by some types of structure pointing backward to a very lowly ancestry. They

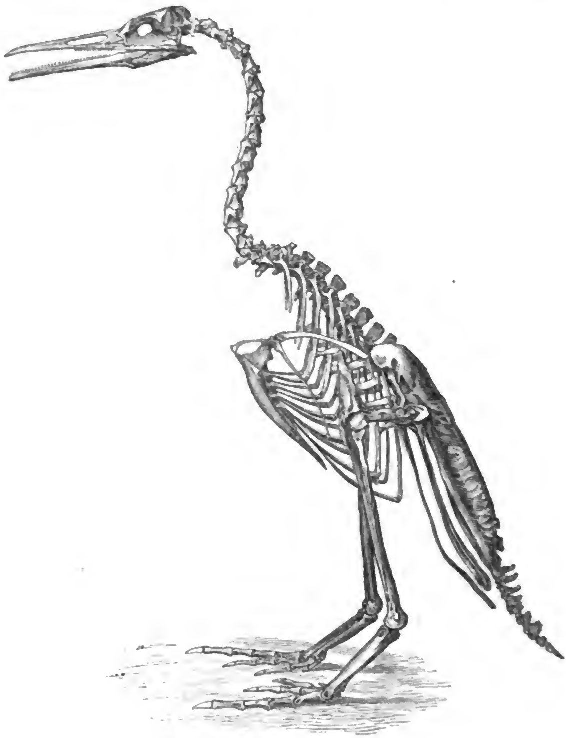


FIG. 398.—CRETACEOUS BIRD.[1]
Hesperornis regalis (Marsh) ($\frac{1}{10}$).

appear to have been small, tern-like birds, with powerful wings but small legs and feet. They possessed reptile-like skulls, with teeth set in sockets, but their vertebræ were bi-concave, like those

[1] For this restoration and Fig. 399, I am indebted to the kindness of my friend Professor Marsh.

of fishes. Altogether the earliest known birds present characters of strong affinity with the Deinosaurs and Pterodactyles.

§ 2. Local Development.

The Cretaceous system in many detached areas covers a large extent of Europe. From the south-west of England it spreads across the north

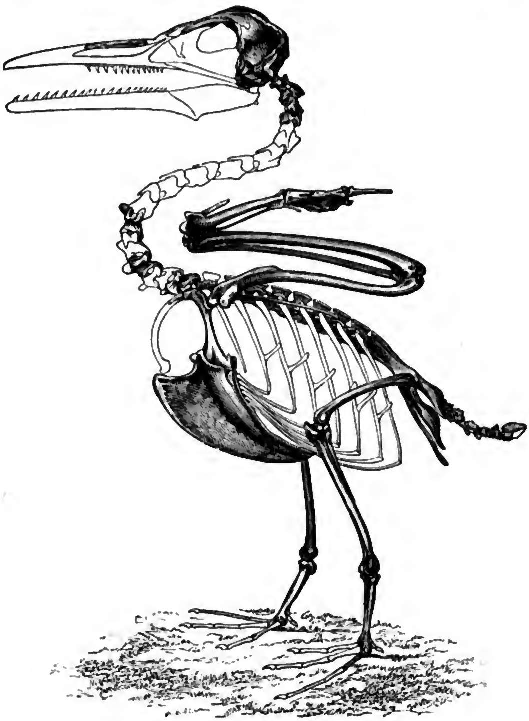


FIG. 399.—CRETACEOUS BIRD.
Ichthyornis victor (Marsh) (½).

of France up to the base of the ancient central plateau of that country. Eastwards it ranges beneath the Tertiary and post-Tertiary deposits of the great plain, appearing on the north side at the southern end of Scandinavia and in Denmark, on the south side in Belgium and Hanover, round the flanks of the Harz, in Bohemia and Poland, eastwards into

Russia, where it covers many thousand square miles, up to the southern end of the Ural chain. To the south of the central axis in France, it underlies the great basin of the Garonne, flanks the chain of the Pyrenees on both sides, spreads out largely over the eastern side of the Spanish table-land, and reappears on the west side of the crystalline axis of that region along the coast of Portugal. It is seen at intervals along the north and south fronts of the Alps, extending down the valley of the Rhone to the Mediterranean, ranging along the chain of the Apennines into Sicily and the north of Africa, and widening out from the eastern shores of the Adriatic through Greece, and along the northern base of the Balkans to the Black Sea, round the southern shores of which it ranges in its progress into Asia, where it again covers an enormous area.

A series of rocks covering so vast an extent of surface must needs present many differences of type, alike in their lithological characters and in their organic contents. They bring before us the records of a time when a continuous sea stretched over the centre and most of the south of Europe, covered the north of Africa, and swept eastwards to the far east of Asia. There were doubtless many islands and ridges in this wide expanse of water, whereby its areas of deposit and biological provinces must have been more or less sharply defined. Some of these barriers can still be traced, as will be immediately pointed out.

The Cretaceous system of Europe has been subdivided as follows:[1]

Upper . .	Danian. Senonian. Turonian. Cenomanian. Gault.
Lower . .	Neocomian, including a prevalent marine type, and also in some parts of the western districts a fluviatile (Wealden) type.

While there is sufficient palæontological similarity to allow a general parallelism to be drawn among the Cretaceous rocks of western Europe, there are yet strongly marked differences pointing to very distinct conditions of life, and probably, in many cases, to disconnected areas of deposit. Having regard to these geographical variations, a distinct northern and southern province, as above stated (p. 802), can be recognized; but Gümbel has proposed a further grouping into three great regions:—(1) the northern province, or area of white chalk with *Belemnitella*, comprising England, northern France, Belgium, Denmark, Westphalia, &c.; (2) the Hercynian province, or area of *Exogyra columba*, embracing Bohemia, Moravia, Saxony, Silesia, and central Bavaria; and (3) the southern province, or area of hippurites, including the regions of France south of the basin of the Seine, the Alps, and southern Europe.[2]

Britain.[3]—The Purbeck beds bring before us evidence of a great change in the geography of England towards the close of the Jurassic period. They show how the floor of the sea in which the thick and varied formations of that period were deposited came to be gradually

[1] See notes on pp. 824, 825.

[2] *Geognost. Beschreib. Ostbayer. Grenzgebirg.*

[3] Consult Conybeare and Phillips, *Geology of England and Wales*, 1822; Fitton, *Ann. Philos.* 2nd ser. viii. 379; *Trans. Geol. Soc.* 2nd ser. iv. 103; Dixon's *Geology of Sussex*, edit. T. Rupert Jones, 1878; Phillips's *Geology of Oxford and the Thames Valley*; recent papers on the English Cretaceous formations are quoted in subsequent footnotes.

elevated, and how into pools of fresh and brackish water the leaves, insects, and small marsupials of the adjacent land were washed down. These evidences of terrestrial conditions are followed in the same region by a vast delta-formation, that of the Weald, which accumulated over the south of England, while the older marine parts of the Cretaceous system were being deposited in the north. Hence two types of sedimentation occur, one where the strata are fluviatile or estuarine (Wealden), the other where they are marine (Neocomian). Arranged in descending order the following are the subdivisions of the English Cretaceous rocks:

TABLE OF THE BRITISH CRETACEOUS SYSTEM.

English Stratigraphical Subdivisions.			*Palæontological Zones.*
	UPPER CRETACEOUS.		Danian, wanting.
Upper Chalk with Flints.	Chalk of Norwich	Senonian.	Zone of *Belemnitella mucronata.* { Horizon of *B. mucronata* alone. " *B. mucronata* and *B. quadrata.*
	" Margate		Zone of *Marsupites ornatus.* { " numerous sponges. " *Inoceramus lingua* and few sponges.
	" Broadstairs . . .		Zone of *Micraster cor-anguinum*, var.
	" Dover		" *M. cor-testudinarium.*
Lower Chalk without Flints.	Hard Nodular Chalk of Dover, &c., "Chalk Rock."	Turonian.	Zone of *Holaster planus.*
	Chalk without flints, Dover, &c. .		" *Terebratulina gracilis.*
	Nodular Chalk of Shakespeare's Cliff, &c.		" *Inoceramus labiatus (mytiloides).*
	Grey Chalk of Folkestone, &c. Totternhoe Stone	Cenomanian.	Zone of *Belemnites plenus.* Zone of *Holaster subglobosus.* { Horizon of *Ammonites rhotomagensis.* " *A. varians.* " *Plocoscyphia mæandrina.*
Chalk Marl.	Chalk Marl		
Chloritic Marl.	Chloritic Marl (Cambridge Greensand)		Zone of "Craie glauconieuse" of France.
Upper Greensand.	Warminster beds, &c. . . .		" *Pecten asper.*
	Blackdown beds, &c. . . .		" *Ammonites inflatus (rostratus).*
Gault.	Upper	Gault.	*Ammonites cristatus, A. auritus, A. lautus.*
	Lower		*Hamites rotundus.* See p. 819.

TABLE OF THE BRITISH CRETACEOUS SYSTEM—*continued.*

English Stratigraphical Subdivisions.				*Palæontological Zones (Marine).*
	Lower Cretaceous. *Southern Type.* (Fluviatile, and in upper part marine.)	*Northern Type.* (Marine.)		
Lower Greensand.	Sands, clays, limestones, &c., in Kent, Surrey, Sussex, Hampshire.	Upper Neocomian, upper 150 feet of Speeton Clay, Yorkshire.	Neocomian.	Upper. *Perna Mulletii*, *Exogyra sinuata*, *&c.*
Wealden.	Weald Clay.	Middle Neocomian, next 150 feet of Speeton Clay, and "Tealby beds."		Middle. Zone of *Pecten cinctus*, *Ancyloceras* beds.
	Hastings sands and clays, passing down into Purbeck beds.	Lower Neocomian, next 200 feet of Speeton Clay.		Lower. Zone of *Ammonites speetonensis*. " *A. noricus*. " *A. astierianus*.

Lower Cretaceous or Neocomian.[1]—Between the top of the Jurassic system and the strata known as the Gault, there occurs an important series of deposits to which, from their great development in the neighbourhood of Neufchatel (Neocomum) in Switzerland, the name of Neocomian has been given. This series, as already remarked, is represented in England by two distinct types of strata. In the southern counties, from the Isle of Purbeck to the coast of Kent, there occurs a vast succession of estuarine and fluviatile sands and clays termed the Wealden series. These strata pass up into a minor marine group known as the Lower Greensand, in which some of the characteristic fossils of the Upper Neocomian rocks occur. The Wealden beds therefore form a fluviatile equivalent of nearly the whole of the continental Neocomian formations, while the Lower Greensand represents the later marginal deposits of the Neocomian sea, which gradually usurped the place of the Wealden estuary. The second type, seen in the tract of country extending from Lincolnshire into Yorkshire, contains the deposits of deeper water forming the westward extension of an important series of marine formations which stretch for a long way into central Europe.

Neocomian.—The marine Neocomian strata of England are well exposed on the cliffs of the Yorkshire coast at Filey, where they occur in a deposit long known as the "Speeton Clay." This deposit has been shown by Mr. Judd to belong partly to the Jurassic and partly to the Neocomian series. The Neocomian portion is divided by him into three formations, as follows:—1. Lower Neocomian (200 feet or more), containing in ascending order the zones of (*a*) *Ammonites astierianus*, (*b*) *Am. noricus*, (*c*) *Am. speetonensis*. Among its fossils are *Toxaster complanatus*, *Ancyloceras puzosianum*, *A. Duvalii*, *A. Emericii*. 2. Middle Neocomian (150 feet), composed of (*a*) Ancyloceras beds, (*b*) Zone of *Pecten cinctus*,

[1] Consult on marine type Judd, *Q. J. Geol. Soc.* xxix. 218; xxvi. 326; xxvii. 207; *Geol. Mag.* vii. 220; *Geology of Rutland*, in *Mem. Geol. Surv.*; Meyer, *Q. J. Geol. Soc.* xxviii. 243; xxix. 70.

and (*c*) Dark clays with few fossils. 3. Upper Neocomian (150 feet or more), consisting of (*a*) Cement beds with numerous fossils (*Perna Mulletii*, *Exogyra sinuata*, &c.); (*b*) Dark blue clays with *Belemnites semicanaliculatus*, &c. (*c*) Black clay with Belemnites; the top of the series not being seen. All these strata are covered unconformably by the Upper Cretaceous groups which successively repose directly upon all the horizons down to the Lower Lias. Owing partly to this circumstance and partly to the thick covering of superficial deposits, no satisfactory sections are seen inland. In Lincolnshire, however, a portion of the Neocomian series comes to the surface from beneath the chalk, consisting of sands, sandstones, clays, and oolitic limestones, which, traced southwards by Tealby, pass into a group of calcareous beds (Tealby series). These strata contain Middle Neocomian fossils. Still further south they become white or brown nearly unfossiliferous sands and sandstones.

Wealden.—In the southern counties a very distinct assemblage of strata is met with.[1] It consists of a vast series of fluviatile or estuarine deposits termed the Wealden, from the Weald of Sussex and Kent where it is best developed, surmounted by a group of marine beds ("Lower Greensand"), in which Upper Neocomian fossils occur. It would appear that the fresh-water conditions of deposit which began in the south of England towards the close of the Jurassic period, when the Purbeck beds were laid down, continued during the whole of the long interval marked by the Lower and Middle Neocomian formations, and only in Upper Neocomian times finally merged into ordinary marine sedimentation. The Wealden series has a thickness of 1800 feet, and consists of the following subdivisions in descending order:

Weald Clay	1000 feet
Hastings Sand group composed of	
3. Tunbridge Wells Sand	140 to 380 „
2. Wadhurst Clay	120 „ 180 „
1. Ashdown Sand	400 or 500 „

These strata precisely resemble the deposits of a modern delta. That such was really their origin is borne out by their organic remains, which include terrestrial plants (*Equisetum*, *Sphenopteris*, *Alethopteris*, *Thuytes*, cycads, and conifers), fresh-water shells (*Unio*, 10 species; *Cyrena*, 5 species; *Cyclas*, *Paludina*, *Melania*, &c.), with a few estuarine or marine forms as *Ostrea* and *Mytilus*, and ganoid fishes (*Lepidotus*) like the gar of American rivers. Among the spoils of the land floated down by the Wealden river were the carcases of huge deinosaurian reptiles (*Iguanodon*, *Hylæosaurus*, *Megalosaurus*, *Vectisaurus*, *Hypsilophodon*), long-necked plesiosaurs, and winged pterodactyles. The deltoid formation in which these remains occur extends in an east and west direction for at least 200 miles, and from north to south for at least 100. Hence the delta must have been not less than 20,000 square miles in area. It has been compared with that of the Quorra; in reality, however, its extent must have been greater than its present visible area, for it has suffered from denudation, and is to a large extent concealed under more recent formations. The river probably descended from the north-west, draining a vast area, of which the existing mountain groups

[1] On the wealden or fluviatile type consult, besides the works quoted on p. 814, Mantell's *Fossils of the South Downs*, 4to, 1822; Topley, *Geology of the Weald*, in *Mem. Geol. Surv.* 8vo, 1875.

of Britain are perhaps merely fragments. The Wealden beds are succeeded conformably by the group of arenaceous strata which have long been known under the awkward name of "Lower Greensand." They consist mainly of yellow, grey, white, and green sands, but include also beds of clay and bands of limestone and ironstone. They have been subdivided in descending order as under:

Folkestone beds	70 to 100 feet
Sandgate beds	75 ,, 100 ,,
Hythe beds	80 ,, 300 ,,
Atherfield Clay resting on Wealden	20 ,, 60 ,,

These strata represent the Upper Neocomian series of the Continent. Among their fossils the following may be mentioned: *Toxaster complanatus*, *Rhynchonella gibbsiana*, *Terebratula sella*, *Exogyra sinuata*, *Gervillia anceps*, *Ostrea frons* (*carinata*), *Pecten quinquecostatus*, *Perna Mulletii*, *Arca Raulini*, *Panopæa plicata*, *Trigonia alæformis*, *Ammonites Deshayesii*, *Ancyloceras gigas*, *Nautilus radiatus*. Of the total number of fossils from the "Lower Greensand" or Upper Neocomian, about 300 in number, only 18 or 20 per cent. pass up into the Upper Cretaceous. This marked palæontological break, taken in connection with an unconformability between the "Lower Greensand" and Gault in the southern counties, and between the top of the Speeton clay and the overlying Hunstanton limestone in the north, shows that a definite boundary-line can be drawn between the lower and upper parts of the Cretaceous system in England.

Upper Cretaceous.—Three leading lithological groups have long been recognized as constituting the Upper Cretaceous series of England. First, a band of clay termed the Gault; second, a variable and inconstant group of sands and sandstones called the "Upper Greensand;" and third, a massive calcareous formation chiefly composed of white chalk. But the foreign nomenclature, founded mainly on palæontological considerations, and given in the foregoing table (p. 815), may now be adopted, as it brings the English Upper Cretaceous groups into recognizable parallelism with their continental equivalents.

Gault.—A dark stiff blue, sometimes sandy or calcareous, clay with layers of pyritous and phosphatic nodules and occasional seams of green sand. It varies from 100 to more than 200 feet in thickness, forming a marked line of boundary between the upper and lower Cretaceous rocks, overlapping the latter and resting sometimes even on the Kimmeridge clay. One of the best sections is that of Copt Point on the coast near Folkestone, where the following subdivisions have been established by Messrs. De Rance and Price:[1]

Upper Greensand.

Upper Gault.

11. Pale grey marl clay (56ft. 3in.), characterized by *Ammonites rostratus* (*inflatus*), *A. Goodhalli*, *Ostrea frons*, *Inoceramus Crispii*.
10. Hard pale marly clay (5ft. 1in.), with *Kingena lima*, *Rostellaria maxima*, *Plicatula pectinoides*, *Pecten raulinianus*, *Pentacrinus Fittoni*, *Cidaris gaultina*.
9. Pale grey marly clay (9ft. 4½in.), with *Inoceramus sulcatus*, *Ammonites varicosus*, *Pholadomya fabrina*, *Pleurotomaria Gibbsii*, *Scaphites æqualis*.
8. Darker clay with two lines of nodules and rolled fossils (9½in.), with *Ammonites cristatus*, *A. Beudanti*, *Pholas sanctæ-crucis*, *Mytilus Gallienuei*, *Cucullæa glabra*, *Cyprina quadrata*.

[1] C. E. De Rance, *Geol. Mag.* v. p. 163; F. G. H. Price, *Q. J. Geol. Soc.* xxx. p. 342.

Lower Gault.

7. Dark clay (6ft. 2in.) highly fossiliferous, with *Ammonites auritus, Nucula bivirgata, N. ornatissima, Aporrhais Parkinsoni, Fusus indecisus, Pterocera bicarinatum.*
6. Dark mottled clay (1ft.), *Ammonites denarius, A. cornutus, Turrilites hugardianus, Necrocarcinus Bechei.*
5. Dark spotted clay (1ft. 6in.), *Ammonites lautus, Astarte dupiniana, Solarium moniliferum, Phasianella ervyna,* numerous corals.
4. Paler clay (4in.), *Ammonites Delaruei, Natica obliqua, Dentalium decussatum, Fusus gaultinus.*
3. Light fawn-coloured clay, "crab-bed" (4ft. 6in.), with numerous carapaces of crustaceans (*Palæocorystes Stokesii, P. Broderipii*), *Pinna tetragona, Hamites attenuatus.*
2. Dark clay marked by the rich colour of its fossils (4ft. 3in.), *Ammonites auritus, Turrilites elegans, Ancyloceras spinigerum, Aporrhais calcarata, Fusus itierianus, Cerithium trimonile, Corbula gaultina, Pollicipes rigidus.*
1. Dark clay, dark greensand, and pyritous nodules (10ft. 1in.), *Ammonites interruptus, Crioceras astierianum, Hamites rotundus.*

Lower Greensand.

Mr. Price remarks that out of 240 species of fossils collected by him from the Gault only 39 are common to the lower and upper divisions, while 124 never pass up from the lower, and 59 appear only in the upper. The lower Gault seems to have been deposited in a sea specially favourable to the spread of gasteropods, of which 46 species occur in that division of the formation. Of these only six appear to have survived into the period of the upper Gault, where they are associated with five new forms. Of the lamellibranch fauna, numbering in all 73 species, 39 are confined to the lower division, four are peculiar to the passage-bed (No. 8), 14 pass up into the upper division, where they are accompanied by 16 new forms.[1] About 46 per cent. of the Gault fauna pass up into the upper Greensand.

Cenomanian.[2]—Under the name of *Upper Greensand* have been comprised sandy strata, often greenish in colour, which are now known to belong to different horizons of the Cretaceous series. If the term is to be retained at all, its use must be accompanied with some palæontological indication of the true position of the beds to which it is applied. According to the recent researches of Dr. C. Barrois the English greensand, as originally defined by Berger, Inglefield, Webster, Fitton, and others, has no such distinct assemblage of fossils as might have been supposed from its lithological characters, but appears to be everywhere divisible into two groups, a lower containing *Ammonites rostratus* (*inflatus*),

[1] *Q. J. Geol. Soc.* xxx. p. 350.

[2] Within the last few years the old lithological subdivisions of the English Upper Cretaceous beds have been found to be wanting in palæontological precision, and are gradually being supplanted by the terms already proposed by D'Orbigny, which have long been in use in France. These terms are here employed, but their equivalents in the old nomenclature will be understood from the table on p. 815. To M. Hébert geology is mainly indebted for the thorough detailed study and classification to which the upper Cretaceous formations of the Anglo-Parisian basin have been subjected. In 1874 he published a short memoir in which the chalk in Kent was subdivided into zones equivalent to those in the Paris basin (*Bull. Soc. Géol. France*, 1874, p. 416). Subsequently the same task was taken up and extended over the rest of the English Cretaceous districts, by Dr. Charles Barrois ("Recherches sur le Terrain Crétacé Supérieur de l'Angleterre et de l'Irlande." Lille, 1876). The first English geologist who appears to have attempted the palæontological subdivision of the chalk was Mr. Caleb Williams (Lewes, 8vo, 1870. *For the Geologists' Association*). See also W. Whitaker, "Geology of the London Basin," *Geol. Survey Memoirs*, vol. iv., and authors there cited. A tolerably full bibliography will be found in Dr. Barrois' volume.

and an upper marked by *Pecten asper.* These strata are well developed in Devonshire and Somerset. There the "Blackdown beds" below, linked with the Gault, contain a numerous fauna, including *Ammonites Goodhalli, Hamites alternatus, Cytherea parva, Venus submersa, Arca glabra, Trigonia alæformis, Pecten laminosus, Janira quinquecostata, J. quadricostata, J. æquicostata, Ostrea (Exogyra) conica, Vermicularia polygonalis*; while the "Warminster beds" above correspond to the "zone of *Holaster nodulosus*" of M. Hébert, and the "zone of *Pecten asper*" of Dr. Barrois, and contain *Ammonites varians, A. Mantelli, A. Coupei, Belemnites ultimus, Pecten asper, Ostrea frons (carinata), Terebratella pectita, Terebratula biplicata, T. squamosa, Rhynchonella compressa, R. latissima, Pseudodiadema Michelini, Peltastes clathratus, Discoidea subucula*, &c. A tolerably abundant series of corals has been obtained from the Devonshire Upper Greensand, no fewer than 21 species having been described.[1]

The so-called Greensand of Cambridge (p. 809), a thin glauconitic marl, with phosphatic nodules and numerous (possibly ice-borne) erratics, was formerly classed with the Upper Greensand, but has recently been shown to be the equivalent of the Chloritic marl, forming really the base of the Chalk marl and lying unconformably upon the Gault, from the denudation of which its rolled fossils have been derived.[2] Further north, at Hunstanton, in Norfolk, the same horizon may be represented by the "Red chalk"—a ferruginous, hard, nodular chalk zone (four feet) at the base of the chalk and resting on the Upper Neocomian "Car-stone," the Gault being absent.

Chloritic Marl.—This name has been applied to a local white or light yellow chalky marl lying below the true Chalk, and marked by the occurrence of grains of glauconite (not chlorite) and phosphatic nodules. It varies up to 15 feet in thickness. Among its fossils are *Ammonites laticlavius, A. Coupei, A. Mantelli, A. varians, Nautilus lævigatus, Turrilites tuberculatus, Solarium ornatum, Plicatula inflata, Terebratula biplicata.* It forms the base of the "*Holaster subglobosus* group," or assise.

Chalk Marl is the name given to an argillaceous chalk forming with the chloritic marl, where the latter is present, the base of the true Chalk formation. This subdivision is well exposed on the Folkestone cliffs, also westward in the Isle of Wight, where a thickness of upwards of 100 feet has been assigned to it. Among its characteristic fossils are *Plocoscyphia mæandrina, Holaster lævis* (var. *nodulosus*), *Rhynchonella Martini, Inoceramus striatus, Lima globosa, Plicatula inflata, Ammonites cenomanensis, A. falcatus, A. Mantelli, A. navicularis, A. varians, Scaphites æqualis, Turrilites costatus.*

Grey Chalk.—The lower part of the Chalk has generally a somewhat greyish tint, often mottled and striped. The subdivision comprising the palæontological zones of *Holaster subglobosus* and *Belemnites plenus* attains its fullest development along the shore-cliffs of Kent, where it attains a thickness of about 200 feet. According to Mr. F. G. H. Price,[3] it is there divisible into five beds. Of these the lowest, eight feet thick (= lower part of the *Ammonites varians* zone), contains among other fossils *Discoidea subucula, Pecten Beaveri, Ammonites varians*; the second bed (11 feet) contains many fossils, including *Ammonites rhotomagensis, A. Man-*

[1] P. Martin Duncan, *Q. J. Geol. Soc.* xxxv. p. 90.

[2] Jukes-Browne, *Q. J. Geol. Soc.* xxxi. p. 272, xxxiii. p. 485; "Geology of Cambridge," *Mem. Geol. Surv.* 1881.

[3] *Q. J. Geol. Soc.* xxiii. p. 436.

telli, *A. lewesiensis* (= part of *A. varians* zone); the third bed (2 feet, 9 inches), also abundantly fossiliferous, contains among other forms *Peltastes clathratus*, *Hemiaster Morrisii*, *Terebratula rigida*, *Rhynchonella mantelliana*, *Ammonites rhotomagensis*, *A. varians;* this and the two underlying beds are regarded as comprising the zone of *Ammonites rhotomagensis* and *A. varians;* the fourth bed, or zone of *Holaster subglobosus* (148 feet), contains among its most characteristic fossils *Discoidea cylindrica*, *Holaster subglobosus*, *Goniaster mosaicus*, and in its upper part *Belemnites plenus;* the fifth bed, or zone of *Belemnites plenus*, consisting of yellowish white gritty chalk (4 feet), forms a well-defined band between the Grey Chalk and the overlying lower subdivision of the White Chalk (Turonian); it contains few fossils, among which are *Belemnites plenus*, *Hippurites* (*Radiolites*) *Mortoni*, *Ptychodus*.

Recent researches by the Geological Survey in Cambridgeshire have shown that in that region the Chalk Marl is covered by a band of harder stone (Totternhoe Stone), passing up into sandy and then nearly pure white chalk, and that these strata, equivalents of the Chalk Marl and Grey Chalk, are probably separated by a palæontological and stratigraphical break from the next overlying (Turonian) member of the series.[1] According to the original classification of M. Hébert, this zone of *Belemnites plenus* is placed at the base of the Turonian group; by Dr. Barrois it is made the summit of the Cenomanian. The latter view receives support from the evidence of a break and considerable denudation above this zone in England.

Turonian (*Lower White Chalk without flints*).—The White Chalk of England and north-west France forms one of the most conspicuous members of the great Mesozoic suite of deposits. It can be traced from Flamborough Head in Yorkshire across the south-eastern counties to the coast of Dorset. Throughout this long course its western edge usually rises somewhat abruptly from the plains as a long winding escarpment, which from a distance often reminds one of an old coast-line. The upper half of the deposit is generally distinguished by the presence of many nodular layers of flint. With the exception of these enclosures, however, the whole formation is a remarkably pure white pulverulent dull limestone, meagre to the touch, and soiling the fingers. Composed mainly of crumbled foraminifera, urchins, molluscs, &c., it must have been accumulated in a sea tolerably free from sediment, like some of the foraminiferal ooze of the existing sea-bed. There is, however, no evidence that the depth of the water at all approached that of the abysses in which the present Atlantic globigerina-ooze is being laid down. Indeed, the character of the foraminifera, and the variety and association of the other organic remains, are not like those which have been found to exist now on the deep floor of the Atlantic, but present rather the characters of a shallow-water fauna. Moreover, the researches of M. Hébert have shown that the chalk is not simply one continuous and homogeneous deposit, but contains evidence of considerable oscillations, and even of occasional emersion and denudation of the sea-floor on which it was laid down. The same observer believes that enormous gaps occur in the upper Cretaceous series of the Anglo-Parisian basin, some of which are to be supplied from the centre and south of France (*postea*, p. 826).

[1] A. J. Jukes-Browne, *Geol. Mag.* 1880, p. 250.

Following the modern classification, we find that the old subdivision of "Chalk without flints" agrees on the whole with the Turonian section of the system. This division, as above remarked, appears in some places to lie unconformably upon the members below it, from which it is further separated by a marked zoological break. Nearly all the Cenomanian species now disappear save two or three cosmopolitan forms. The echinoderms and brachiopods are entirely replaced by new species.[1] Not only is the base of the Turonian group defined by a stratigraphical hiatus, but its summit is marked by the Nodular Chalk of Dover and the hard Chalk-rock, which appear to indicate another stratigraphical break in what was formerly believed to be an uninterrupted deposit of chalk. The three Turonian palæontological zones, so well established in France, are also traceable in England. As exposed in the splendid Kent cliffs, the base of the English beds is formed by a well-marked band (32 feet) of hard gritty chalk, made up of fragments of *Inocerami* and other organisms. Fossils are here scarce; they include *Inoceramus labiatus* (which begins here), *Rhynchonella Cuvieri*, *Echinoconus subrotundus*, *Cardiaster pygmæus*. Above this basement bed lies the massive chalk without flints, full of fragments of *Inoceramus labiatus*, with *I. Cuvieri*, *Terebratula semiglobosa*, *Terebratulina gracilis*, *Echinoconus subrotundus*, &c. The lower 70 feet or so include the zone of *Inoceramus labiatus*, the next 90 or 100 feet that of *Terebratulina gracilis*, and the upper 50 or 60 feet, containing layers of black flints, that of *Holaster planus*. At the top comes the remarkably constant band of hard cream-coloured limestone known as the "Chalk-rock," varying from a few inches to 10 feet in thickness. Its upper surface is generally well defined, sometimes even suggestive of having been eroded, but it shades down into the lower chalk.[2]

Senonian (*Upper Chalk with flints*).—This massive formation is composed of white pulverulent and usually tolerably pure chalk, with scattered flints, which, being arranged in the lines of deposit, serve to indicate the otherwise indistinct stratification of the mass. It has been generally regarded by English geologists as a single formation, with great uniformity of lithological characters and fossil contents. Mr. Whitaker, however, has shown that distinct lithological platforms occur in it, and more recent researches, especially by MM. Hébert and Barrois, have brought to light the same zones that occur in the Paris basin. Of these the lowest, or that of the Micrasters (Broadstairs and St. Margaret's chalk), is most widely spread, the others having suffered most from denudation. It is well exposed along the cliffs of Kent at Dover, and also in the Isle of Thanet. At Margate its thickness has been ascertained by boring to be 265 feet. It contains two zones, in the lower of which the characteristic urchin is *Micraster cor-testudinarium*, while in the upper it is *M. cor-anguinum*. Near the top of the Micraster group of beds in the Isle of Thanet, lies a remarkable seam of flint about three or four inches thick, forming a nearly continuous floor, which has been traced southwards at the top of the cliffs between Deal and Dover. Again, on the coast of Sussex, the same horizon in the chalk is defined by a corresponding band of massive flattened flints. The traces of emersion and erosion observed by M. Hébert in the Paris chalk are

[1] Jukes-Browne, *Geol. Mag.* 1880, p. 250.

[2] Whitaker, *Mem. Geol. Surv.* iv. p. 46. Jukes-Browne, *Geol. Mag.* 1880, p. 251. A similar band occurs in Normandy.

regarded by Dr. Barrois as equally distinct on the English side of the Channel in the form of surfaces of hardened and corroded chalk. One of these surfaces marks the upper limit of the Micraster group on the Sussex coast, where it consists of a band of yellowish hardened and corroded chalk about six inches thick, containing rolled green-coated nodules of chalk.[1] A similar hardened, corroded, tubular band forms the same limit in the Isle of Thanet. Among the fossils of the Micraster division the following may be mentioned: *Micraster cor-testudinarium, M. cor-anguinum, Cidaris clavigera, Echinocorys gibbus, Echinoconus conicus, Epiaster gibbus, Terebratulina gracilis, Terebratula semiglobosa, Ostrea vesicularis, Inoceramus involutus.*

The middle division, or Margate chalk, has been named the Marsupite zone by Dr. Barrois from the abundance of these crinoids. It attains a thickness of about 80 feet in the Isle of Thanet, where it contains few or no flints, and upwards of 400 feet in the Hampshire basin, where flints are numerous. Among its fossils are *Amorphospongia globosa, Bourgueticrinus ellipticus, Marsupites ornatus, M. Milleri, Micraster cor-anguinum, Echinoconus conicus, Echinocorys gibbus, Cidaris clavigera, C. sceptrifera, Thecideum Wetherelli, Terebratula semiglobosa, Rhynchonella plicatilis, Terebratulina striata, Spondylus (Lima) spinosus, S. dutempleanus, Pecten cretosus, Ostrea vesicularis, O. hippopodium, Inoceramus lingua* (and several others), *Belemnites verus, B. Merceyi, Ammonites leptophyllus.*

The highest remaining group, or Norwich chalk, forms the *Belemnitella* zone so well marked in northern Europe. It attains a thickness of from 100 to 160 feet in the Hampshire basin (Portsdown Chalk), is absent from that of London, but reappears in Norfolk, where it attains its greatest development. It is at Norwich a white crumbling chalk with layers of black flints. Among its fossils are *Parasmilia centralis, Trochosmilia laxa, Cyphosoma magnificum, Salenia geometrica, Echinocorys ovatus, Rhynchonella octoplicata, R. limbata, Terebratula carnea, T. obesa, Ostrea lunata, Belemnitella mucronata, B. quadrata.*

The uppermost division, or Danian, of the Continental chalk appears to be absent in England, unless its lower portions are represented by some of the uppermost beds of the Norwich chalk.

The Cretaceous system is sparingly represented in Ireland and Scotland. Under the Tertiary basaltic plateau of Antrim there lies an interesting series of deposits which in lithological aspect differ greatly from their English equivalents, and yet from their fossil contents can be satisfactorily paralleled with the latter. They are thus arranged:[2]

Hard white limestone	65 to 100 feet	= zone of Belemnitella mucronata.	Senonian.
" "	13 " 16 "	" Marsupites.	
Chloritic chalk	3 " 6½ "	" Micrasters	
Chloritic sand and sandstone	3 " 16 "	" Holaster planus. " Terebratulina gracilis.	Turonian.
Grey marls and yellow sandstones	3 " 30 "	" Holaster subglobosus.	Cenomanian.
Glauconitic sand	6 " 10 "	" Pecten asper.	

[1] Barrois, *Terrain Crétacé de l'Angleterre*, &c., 1876, p. 21.
[2] Barrois, *Op. cit.* p. 216.

In the west of Scotland also relics of the same type of Cretaceous formations have been preserved under the volcanic plateaux of Mull and Morven. They contain the following subdivisions in descending order:[1]

White marly and sandy beds with thin seams of lignite	20 feet
Hard white chalk with *Belemnitella mucronata*, &c................	10 "
Thick white sandstones with carbonaceous matter..................	100 "
Glauconitic sands and shelly limestones, *Pecten asper*, *Exogyra conica*, *Janira quinquecostata*, *Nautilus deslongchampsianus*, &c.	60 "

France and Belgium.[2]—The Cretaceous system so extensively developed in western Europe is distributed in large basins, which, on the whole, correspond with those of the chief rivers. Thus in France there are the basins of the Seine or of Paris, of the Loire or of Touraine, of the Rhone or of Provence, and of the Garonne or of Aquitania, including all the area up to the slopes of the Pyrenees. In most cases these areas present such lithological and palæontological differences in their Cretaceous rocks as to indicate that they may have been to some extent even in Cretaceous times distinct basins of deposit.

Neocomian.[3]—A threefold subdivision of this series of deposits has been traced both in the Paris basin and in the southern provinces. The lowest group, in Marne, Haute Marne, Meuse, &c., consists of sands, marls, spatangus-limestone with *Spatangus*, *Toxaster complanatus*, *Perna Mulletii*, and oyster-clays (*Ostrea Leymeriei*). In the south and east of France it assumes much greater dimensions and consists mainly of limestones, which towards the base contain *Terebratula diphya* (*janitor*, see ante, p. 800), *Ammonites macilentus*, in their middle portions *Belemnites dilatatus*, *Ostrea Couloni*, *Spatangus*, and in their higher zones *Toxaster complanatus*. The middle group, or "Urgonien" of D'Orbigny, consists of fresh-water clays, sands, and ironstones in the northern area, but in the south expands into a massive series of limestones with *Chama* (*Caprotina*) *ammonia*, *Requienia* (*Caprotina*) *Lonsdaleii*, *Pteroceras pelagi*, *Panopæa irregularis*, *Terebratula sella*. The upper group, or "Aptien" of D'Orbigny, is composed in the Paris basin of plicatula-clays, with *Ostrea aquila*, *Plicatula placunea*, *Exogyra sinuata*, *Rhynchonella lata*, *Ancyloceras matheronianum*, *Ammonites fissicostatus*, *A. nisus*, and in Haute Marne contains fresh-water beds with *Paludina*, *Cyclas*, &c.; in the Mediterranean basin it consists of marls (Marnes aptiennes) and sandstones, with similar fossils. In the

[1] Judd, *Q. J. Geol. Soc.* xxxiv. p. 736.

[2] The Cretaceous system has been the subject of prolonged study by the geologists of France, and has given rise to considerable differences of nomenclature. The main formations recognized and named by D'Orbigny have been generally adopted. But great diversity of opinion exists as to the names and limits of the lesser groups. There has been a tendency to excessive elaboration of subdivisions, as may be seen in the classification proposed by M. Coquand. The minor sections of the geological record must always be of but local significance, and it is to be regretted when they are treated as of any higher importance. M. Hébert has wisely refrained from burdening geological nomenclature with a long list of new names for local developments of strata, contenting himself with employing D'Orbigny's names for the formations, and subdividing these into upper, middle, and lower. The student will find some of the rival systems of classification collected by Mr. Davidson, *Geol. Mag.* vi. (1869).

[3] See D'Archiac, *Mém. Soc. Géol. France*, 2e sér. ii. p. 1; Raulin, *Op. cit.* p. 219; Ebray, *Bull. Soc. Géol. France*, 2e sér. xvi. p. 213; xix. p. 184; Cornuel, *Bull. Soc. Geol. France*, 2e sér. xvii. p. 742; 3e sér. ii. p. 371; Hébert, *Op. cit.* 2e sér. xxiv. p. 323; xxviii. p. 137; xxix. p. 394; Coquand, *Op. cit.* xxiii. p. 561; Rouville, *Op. cit.* xxix. p. 723; Bleicher, *Op. cit.* 3e sér. ii. p. 21; Toucas, *Op. cit.* iv. p. 315.

north of France and Belgium the Cretaceous system is underlaid by certain clays, sands, and other deposits belonging to a Continental period of older date than the submergence of that region beneath the sea in which were deposited the uppermost Neocomian beds. These scattered Continental deposits have been grouped under the name of Aachenian.[1] On the coast the Folkestone type of Neocomian beds is well seen between Boulogne and Calais.

Gault or *Albian*.[2]—This characteristic and easily-traced subdivision of the Cretaceous series appears on the coast opposite to Folkestone with the same lithological and palæontological features as on the English side of the Channel. The pyritous clays sweep round the northern and eastern margin of the great Paris basin, and appear likewise on the west near Havre. They have also been found in deep wells around Paris. They contain the following subdivisions in descending order:

3. Zone of *Ammonites inflatus*—Glauconitic clay of Sancerre, Ochre of Puisaye, Marls of Larrivour, "gaize" (a porous sandstone slightly impregnated with silica soluble in alkali) of the Argonne, upper clay of Wissant, &c. It has yielded 141 species of fossils, among which are *Ammonites inflatus*, *A. splendens*, *A. auritus*, *Nautilus radiatus*, *Hamites intermedius*, *Natica gaultina*, *Rostellaria carinata*, *Cardita tenuicosta*, *Inoceramus sulcatus*, *Pecten raulinianus*, *Janira quinquecostata*, *Plicatula pectinoides*, *Ostrea canaliculata*, *Terebratula dutempleana*, *Kingena lima*.
2. Zone of *Ammonites interruptus*, consisting of dark clays with nacreous shells, sands, and sandstone. *Ammonites interruptus*, *A. splendens*, *A. lautus*, *A. denarius*, *Hamites rotundatus*, *Natica gaultina*, *Cardita tenuicosta*, *Inoceramus concentricus*, *Plicatula pectinoides*, &c.
1. Zone of *Ammonites mammillaris*—green sand sometimes containing phosphatic nodules—*Ammonites mammillaris*, *A. raulinianus*, *A. Beudanti*, *Natica gaultina*, *Pterocera bicarinatum*, *Inoceramus Salomoni*, *Plicatula radiola*, *Rhynchonella gibbsiana*, &c.

The *Upper Cretaceous* rocks of France have been the subject of prolonged and detailed study by the geologists of that country.[3] The northern tracts form part of the Anglo-Parisian basin, in which the upper Cretaceous rocks of Belgium and England were laid down. The same palæontological characters, and even in great measure the same lithological composition, prevail over the whole of that wide area, which belongs to the northern Cretaceous province of Europe. Apparently only during the early part of the Cenomanian period, that of the Rouen chalk, did the Anglo-Parisian basin communicate with the wider waters to the south, which were bays or gulfs freely opening to the main Atlantic. In these tracts a notably distinct type of Cretaceous deposits was accumulated, which, being that of the main ocean, covers a much larger geographical area and contains a much more widely diffused fauna than are presented by the more limited and isolated northern basin. There are few more striking contrasts between contemporaneously formed rocks in

[1] On the Aachenian deposits see Dumont, *Terrains Crétacés et Tertiaires* (edited by M. Mourlon, 1878), vol. i. pp. 11–52.

[2] See besides the works already cited, Barrois, *Bull. Soc. Géol. France*, 2e sér. iii. 707; *Ann. Soc. Géol. du Nord*, ii. p. 1; Renevier, *Bull. Soc. Géol. France*, 2e sér. iii. 704.

[3] Notably by MM. Hébert, Toucas, Coquand, and Cornuel. As already stated considerable differences exist among French and Swiss geologists as to the nomenclature and the lines of demarcation between the upper Cretaceous formations, arising doubtless in great part from the varying aspect of the rocks themselves according to the region in which they are studied. I have followed mainly M. Hébert.

adjacent areas of deposit than that which meets the eye of the traveller who crosses from the basin of the Seine to those of the Loire and Garonne. In the north of France and Belgium soft white chalk covers wide tracts presenting the same lithological and scenic characters as in England. In the centre and south of France the soft chalk is replaced by hard limestone, with comparatively few sandy or clayey beds. This mass of limestone attains its greatest development in the southern part of the department of the Dordogne, where it is said to be about 800 feet thick. The lithological differences, however, are not greater than those of the fossils. In the north of France, Belgium, and England, the singular molluscan family of the *Hippuritidæ* or *Rudistes* appears only occasionally and sporadically in the Cretaceous rocks, as if a stray individual had from time to time found its way into the region, but without being able to establish a colony there. In the south of France, however, the hippurites occur in prodigious quantity, often mainly composing the limestones, hence called hippurite limestone (Rudisten-Kalk). They attained a great size, and seem to have grown on immense banks like our modern oyster. They appear in successive species on the different stages of the Cretaceous system, and can be used for marking palæontological horizons, as the cephalopods are employed elsewhere. But while these lamellibranchs played so important a part throughout the Cretaceous period in the south of France, the numerous ammonites and belemnites, so characteristic of the Chalk in England, were comparatively rare there. The very distinctive type of hippurite limestone has so much wider an extension than the northern or Chalk type of the upper Cretaceous system that it should be regarded as really the normal development. It ranges through the Alps into Dalmatia, and round the great Mediterranean basin far into Asia.

Cenomanian (Craie glauconieuse).—According to the classification of M. Hébert this formation is composed of two groups: 1st, Lower or Rouen chalk, equivalent to the upper greensand and grey chalk of England. In the northern region of France and Belgium it consists of the following subdivisions: *a.* a lower group or *assise* of glauconitic beds like the English upper greensand, containing *Ammonites inflatus* below and *Pecten asper* above; *b.* Middle glauconitic chalk with *Turrilites tuberculatus, Holaster carinatus*, &c., probably equivalent to the English Chloritic Marl and Chalk Marl; *c.* Upper hard, somewhat argillaceous, grey chalk with *Holaster subglobosus;* the threefold subdivision of this assise already given is well developed in the north of France; *d.* Calcareous marls with *Belemnites plenus.* 2nd. Upper or marine sandstone; according to M. Hébert this group is wanting in the northern region of France, England, and Belgium. In the old province of Maine it consists of sands and marls with *Anorthopygus orbicularis, Exogyra* (*Ostrea*) *columba, Trigonia*, and *Ostrea.* Further south these strata are replaced by limestones with hippurites (*Caprina adversa*), which extend up into the Pyrenees and eastwards across the Rhine into Provence.[1]

Turonian (Craie Marneuse).—This formation presents a very different facies according to the part of the country where it is examined. In the northern basin, according to M. Hébert, only its lower portions occur, separated by a notable hiatus from the base of the Senonian series,

[1] See a memoir on the Upper Cretaceous rocks of the basin of Uchaux (Provence) by Hébert and Toucas, *Ann. Sciences Géol.* vi. (1875).

and consisting of marly chalk with *Inoceramus labiatus*, *I. Brongniarti*, *Ammonites nodosoides*, *A. peramplus*, *Terebratulina gracilis*. He places the zone of *Holaster planus* at the base of the Senonian groups, and believes that in the hiatus between it and the Turonian beds below the greater part of the Turonian series is really wanting in the north. On the other hand, Dr. Barrois and others would rather regard the zone of *Holaster planus* as the top of the Turonian series. In the north of France, as in England, it is a division of the White Chalk, containing *Ammonites peramplus*, *Scaphites Geinitzii*, *Spondylus spinosus*, *Inoceramus inæquivalvis*, *Terebratula semiglobosa*, *Holaster planus*, *Ventriculites moniliferus*, &c. Strata with *Inoceramus labiatus*, marking the base of the Turonian groups, can be traced through the south and south-east of France into Switzerland. These are overlaid by marls, sandstones, and massive limestones with *Exogyra* (*Ostrea*) *columba* and enormous numbers of hippurites (*Hippurites cornuvaccinum*, *Radiolites cornupastoris*, &c.). These hippurite limestones sweep across the centre of Europe and along both sides of the great Mediterranean basin into Asia, forming one of the most distinctive landmarks for the Cretaceous system.

Senonian.—This formation is most fully developed in the northern basin, where it consists mainly of white chalk separable into the two divisions of, 1st, Micraster group, composed of chalk beds, in the lower of which *Micraster cor-testudinarium* and in the upper *M. cor-anguinum* is the prevalent urchin. The same palæontological facies occurs in this and the other group as in the corresponding strata of England already described. 2nd. Belemnitella group with *B. quadrata* in a lower zone, and *B. mucronata* (Meudon chalk) in a higher. In the south and south-east of France the corresponding beds are partly marine, partly fresh-water, and contain beds of lignite.

Danian.—This subdivision of the Cretaceous system appears to be developed only in the northern basin. In the neighbourhood of Paris and in the Departments of Oise and Marne a rock long known as the Pisolitic Limestone occurs in patches, lying unconformably on the White Chalk. The long interval which must have elapsed between the highest Senonian beds and this limestone is indicated not only by the evidence of great erosion of the chalk previous to the deposit of the limestone, but also by the marked palæontological break between the two rocks. The general aspect of the fossils resembles that of the older Tertiary formations, but among them are some undoubted Cretaceous species. In the south-east of Belgium the Danian series is well exposed, resting unconformably on a denuded surface of chalk. In Hainault it consists of successive bands of yellowish or greyish chalk, between some of which there are surfaces of denudation, with perforations of boring molluscs, so that it contains the records of a prolonged period (chalk of St. Vaast, Obourg, Nouvelles, Spienne, and Ciply). Among the fossils are *Belemnitella mucronata*, *Baculites Faujasii*, *Nautilus Dekayi* (but no *Ammonites*, *Hamites*, or *Turrilites*), *Inoceramus Cuvieri*, *Ostrea flabelliformis*, *O. lateralis*, *O. vesicularis*, *Crania ignabergensis*, *Terebratulina striata*, *Fissurirostra Palissii* (characteristic), *Radiolites ciplyanus*, *Eschara* several species and in great numbers, *Ananchytes ovatus*, *Holaster granulosus*. The well-known chalk of Maestricht is equivalent to part of these strata, but appears to embrace also a higher horizon containing *Hemipneustes striato-radiatus*, *Crania ignabergensis*, *Terebratulina striata*, *Fissurirostra pectiniformis*, *Ostrea*

lunata, *O. vesicularis*, *Janira quadricostata*, and numerous remains of *Mosasaurus* and of chelonians, together with *Voluta*, *Fasciolaria*, and other characteristically Tertiary genera of molluscs.[1] Similar strata and fossils occur at Faxoe, Denmark. The terrestrial flora in the highest Cretaceous series at Aix-la-Chapelle has been already referred to (p. 803).

Germany.—The Cretaceous deposits of Germany, Denmark, and the south of Sweden were accumulated in the same northern province with those of Britain, the north of France, and Belgium, for they present on the whole the same palæontological succession and even to a considerable extent the same lithological characters. It would appear that the western part of this region began to subside before the eastern, and attained a greater amount of depression beneath the sea. In proof of this statement it may be mentioned that the Neocomian clays of the north of England extend as far as the Teutoburger Wald, but are absent from the base of the Cretaceous system in Saxony and Bohemia. In north-west Germany Neocomian strata under the name of Hils appear at many points between the Isle of Heligoland (where representatives of part of the Speeton clay and the Hunstanton red chalk occur), and the east of Brunswick, indicative of what was, doubtless, originally continuous deposit. In Hanover they consist of a lower series of conglomerates (Hils-conglomerat), and an upper group of clays (Hils-thon). Appearing on the flanks of the hills which rise out of the great drift-covered plains, they attain their completest development in Brunswick, where they attain a total thickness of 450 feet, and consist of a lower group of limestone and sandy marls, with *Toxaster complanatus*, *Exogyra Couloni* (*sinuata*), *Ammonites bidichotomus*, *A. astierianus*, and many other fossils; a middle group of dark blue clays with *Belemnites brunswicensis*, *Ammonites nisus*, *Ancyloceras Emmerici*, *Exogyra Couloni* (*sinuata*), &c., and an upper group of dark and whitish marly clays with *Ammonites Martini*, *A. Deshayesi*, *A. nisus*, *Belemnites Ewaldi*, *Toxoceras royerianum*, *Crioceras*, &c.[2] Below the Hils-thon in Westphalia, the Harz, and Hanover, the lower parts of the true marine Neocomian series are replaced by a massive fluviatile formation corresponding to the English Wealden, and divisible into two groups: 1st, Diester sandstone (600 feet), like the Hastings sand of England, consisting of fine light yellow or grey sandstone, dark shales, and seams of coal varying from mere partings up to workable seams of three and even more than six feet in thickness. These strata are full of remains of terrestrial vegetation (*Equisetum*, *Baiera*, *Oleandrideum*, *Laccopteris*, *Sagenopteris*, *Anomozamites*, *Pterophyllum*, *Podozamites*, and a few conifers), also shells of fresh-water genera (*Cyrena*, *Paludina*), cyprids, and remains of *Lepidotus* and other fishes; 2nd, Weald clay (65 to 100 feet) with thin layers of sandy limestone (*Cyrena*, *Cyclas*, *Unio*, *Melania*, *Cypris*, &c.[3]). The Gault or Albian of north-western Germany consists, according to Von Strombeck, of two groups of strata. The lower of these, apparently unrepresented in England, consists of a lower clay with the zone of *Ammonites milletianus*, and an upper clay with *Ammonites tardefurcatus*. The

[1] Dumont, *Mém. Terrains Crétacés*, &c., 1878. Mourlon, *Géol. de la Belgique*, 1880.

[2] Von Strombeck, *Zeitsch. Deutsch. Geol. Ges.* i. p. 462; xiii. 20; *N. Jahrb.* 1855, pp. 159, 644; Judd, *Q. J. Geol. Soc.* xxvi. p. 343.

[3] W. Dunker, *Ueber den norddeutsch. Wälderthon, u. s. w.*, Cassel, 1844; Dunker and Von Meyer, *Monographie der norddeutsch. Wälderbildung, u. s. w.*, Brunswick, 1846; Heinrich Credner, *Ueber die Gliderung der oberen Jura und der Wealdenbildung in nordwestlichen Deutschland*, Prague, 1863.

higher contains at its base a clay with *Belemnites minimus*, and at its top the widely diffused and characteristic "Flammenmergel"—a pale clay with dark flame-like streaks containing the zone of *Ammonites inflatus*.[1]

The upper Cretaceous rocks of Germany present the greatest lithological contrast to those of France and England, yet they contain so large a proportion of the same fossils as to show that they belong to the same period, and the same area of deposit. The Cenomanian formation consists in Hanover of earthy limestones and marls, which traced southward are replaced in Saxony and Bohemia by glauconitic sandstones (Unter-Quader) and limestone (Unter-Plänerkalk). The lowest parts of the formation in the Saxon, Bohemian, and Moravian areas are marked by the occurrence in them of clays, shales, and even thin seams of coal (Pflanzen-Quader), containing abundant remains of a terrestrial vegetation which possesses great interest, as it contains the oldest known forms of hard-wood trees (willow, ash, elm, laurel, &c.). The Turonian beds, traced eastwards, from their chalky and marly condition in the Anglo-Parisian Cretaceous basin, change in character, until in Saxony and Bohemia they consist of massive sandstones (Mittel-Quader) with limestones and marls (Mittel-Pläner). In these strata the occurrence of such fossils as *Inoceramus labiatus*, *I. Brongniarti*, *Ammonites peramplus*, *Scaphites Geinitzii*, *Spondylus* (*lima*) *spinosus*, *Terebratula semiglobosa*, &c., shows their relation to the Turonian of the west. The Senonian group presents a yet more extraordinary variation in its eastern prolongation. The soft upper chalk of England, France, and Belgium, traced into Westphalia, passes into sands, sandstones, and calcareous marls, the sandy strata increasing southwards till they assume the gigantic dimensions which they present in the gorge of the Elbe and throughout the picturesque region known as Saxon Switzerland (Ober-Quader). The horizon of these strata is well shown by such fossils as *Belemnitella quadrata*, *B. mucronata*, *Nautilus danicus*, *Marsupites ornatus*, *Bourgueticrinus ellipticus*, *Crania ignabergensis*, &c.

Switzerland and the Chain of the Alps.[2]—This area is included in the southern basin of deposit. In Switzerland the Neocomian groups are so well developed that they have thence received their collective name. Their average thickness there in the region of the Jura is about 130 feet, but they greatly exceed this in the Neufchatel district. They consist of blue marls (Marnes de Hauterive) with *Toxaster complanatus*, *Rhynchonella depressa*, &c., surmounted by a yellow bedded limestone. In the Alpine region the Neocomian formation is represented by several hundred feet of marls and limestones, which form a conspicuous band in the mountainous range separating Berne from Wallis, and thence into Eastern Switzerland and the Austrian Alps (Spatangenkalk, Schrattenkalk). Some of these massive limestones are full of hippurites of the *Caprina* group (Caprotinenkalk with *Caprotina Lonsdalei*, *Radiolites neocomiensis*, &c.), others abound in polyzoa (Bryozoenkalk), others in foraminifera (Orbitolitenkalk). The Gault is recognizable as a thin band of greenish sandstone and marls, which have long been known for their numerous fossils (Perte du Rhône, St. Croix). They are traceable in the Swiss Jura and the Alps of Savoy. In the Vorarlberg and

[1] *Geol. Mag.* vi. (1869), p. 261.

[2] Studer's *Geologie der Schweiz;* Gümbel, *Geognostische Beschreib. Bayer. Alpen*, vol. i. p. 517 *et seq.*; *Geognostische Beschreib. des Ostbayer. Grenzegebirg.* 1868, p. 697; Von Hauer's *Die Geologie der Oesterr. Ungar. Monarchie*, 1878, p. 505, *et seq.*

Bavarian Alps their place in taken by calcareous glauconitic beds and the Turrilite greensand (*T. Bergeri*); but in the eastern Alps they have not been recognized.

One of the most remarkable formations of the Alpine regions is the enormous mass of sandstone which, under the names of Flysch and Vienna sandstone, stretches from the south-west of Switzerland through the northern zone of the mountains to the plains of the Danube at Vienna. Fossils are exceedingly rare in these rocks, the most frequent being fucoids, which afford no clue to the geological age of their enclosing strata. That the older portions in the eastern Alps are Cretaceous, however, is indicated by the occurrence in them of occasional *Inocerami*, and by their interstratification with true Neocomian limestone (Aptychenkalk). The definite subdivisions of the Anglo-Parisian Upper Cretaceous rocks cannot be applied to the structure of the Alps, where the formations are of a massive and unusually calcareous nature. In the Vorarlberg they consist of massive limestones (Seewenkalk) and marls (Seewenmergel), with *Ammonites Mantelli*, *Turrilites costatus*, *Inoceramus striatus*, *Holaster carinatus*, &c. In the north-eastern Alps they present a remarkable facies in the Gosau beds, consisting of a variable and locally developed group of marine marls, sandstones, and limestones, with occasional intercalations of coal-bearing fresh-water beds. These strata rest unconformably on all rocks more ancient than themselves, even on older Cretaceous groups. They have yielded about 500 species of fossils, of which only about 120 are found outside of the Alpine region, chiefly in Turonian, partly in Senonian strata. Much discussion and a copious literature has been devoted to the history of these deposits.[1] The loosely imbedded shells suggested a Tertiary age for the strata; but their banks of corals, sheets of orbitolite- and hippurite-limestone, and beds of marl with Ammonites, Inocerami, and other truly Cretaceous forms, have left no doubt as to their really upper Cretaceous age. Among their subdivisions the zone of *Hippurites cornuvaccinum* is recognizable. From some lacustrine beds of this age, near Wiener Neustadt, a large collection of reptilian remains has been obtained, including deinosaurs, chelonians, a crocodile, a lizard, and a pterodactyle—in all fourteen genera and eighteen species.[2] Probably more or less equivalent to the Gosau beds are the massive hippurite-limestones and certain marls containing *Belemnitella mucronata*, *Ananchytes ovatus*, &c., of the Salzkammergut and Bavarian Alps.[3] The upper Cretaceous rocks of the south-eastern Alps are distinguished by their hippurite-limestones (Rudistenkalk) with shells of the *Hippurites* and *Radiolites* groups, while the lower Cretaceous limestones are marked by those of the *Caprina* group (Caprotinenkalk). They form ranges of bare white, rocky, treeless mountains perforated with tunnels and passages (Dolinen).

Basin of the Mediterranean.—The southern type of the Cretaceous system attains a great development on both sides of the Mediter-

[1] See among other memoirs, Sedgwick and Murchison, *Trans. Geol. Soc.* 2nd ser. iii.; Reuss, *Denkschrift. Akad. Wien.* vii. 1; *Sitzb. Akad. Wien.* xi. 882; Stoliczka, *Sitzb. Akad. Wien.* xxviii. 482; lii. 1; Zekeli, *Abhandl. Geol. Reichsanst. Wien.* i. 1; F. von Hauer, *Sitzb. Akad. Wien.* liii. 300; *Palæont. Oesterreich.* i. 7; *Die Geologie*, p. 516; Zittell, *Denkschrift. Akad. Wien.* xxiv. 105; xxv. 77; Bünzel, *Abhandl. Geol. Reichsanst.* v. 1; Gümbel, *Geognostische Beschreib. Bayerisch. Alpen*, 1861, p. 517, *et seq.*

[2] Seeley, *Q. J. Geol. Soc.* 1881, p. 620.

[3] See Gümbel, *Op. cit.* He gives a table of correlations for the European Cretaceous rocks with those of Bavaria in his *Geognost. Beschreib. Ostbayer. Grenzgeb.* p. 700, 701.

ranean basin. The hippurite limestones of the south and south-east of France are prolonged into Italy and Greece, whence they range into Asia Minor and into Asia. Cretaceous formations appear likewise in Sicily and cover a vast area in the north of Africa. In the desert region south of Algiers they extend as vast plateaux with sinuous lines of terraced escarpments.[1]

India.—The hippurite limestone of south-eastern Europe is prolonged into Asia Minor, and occupies a vast area in Persia. It has been detected here and there among the Himalaya Mountains in fragmentary outliers. Southward of these marine strata there appears to have existed in Cretaceous times a wide tract of land corresponding on the whole with the present area of the Indian peninsula, but not improbably stretching south-westwards so as to unite with Africa. On the south-eastern side of this area the Cretaceous sea extended, for near Trichinopoly and Pondicherry a series of marine deposits occur corresponding to the European Upper Cretaceous formations, with which they have 16 per cent. of fossil species in common. Similar strata with many of the same fossils occur on the African coast in Natal. The most remarkable episode of Cretaceous times in the Indian area was undoubtedly the colossal outpouring of the Deccan basalts. These rocks, lying in horizontal, or nearly horizontal, sheets, attain a vertical thickness of from 4000 to 5000 feet, and where thickest 6000 feet or more. They cover an area estimated at 200,000 square miles, though their limits have no doubt been reduced by denudation. Their oldest beds lie slightly unconformably on Cenomanian rocks, and in some places appear to be regularly interstratified with the uppermost Cretaceous strata. The occurrence of remains of fresh-water molluscs, land-plants, and insects, both in the lowest and highest parts of the volcanic series, proves that the lavas must have been subaerial. This is one of the most gigantic outpourings of volcanic matter in the world.[2]

North America.—Recent surveys of the western Territories of the United States and of British Columbia have greatly increased our knowledge of the Cretaceous system on the American continent, where it is now known to cover a vast expanse of surface, and to reach an enormous thickness. Sparingly developed in the eastern States, from New Jersey into South Carolina, it spreads out over a wide area in the south, stretching round the end of the long Palæozoic ridge from Georgia through Alabama and Tennessee to the Ohio; and reappearing from under the Tertiary formations on the west side of the Mississippi over a large space in Texas and the south-west. Its greatest development is reached in the western States and Territories of the Rocky Mountain region—Wyoming, Utah, and Colorado, whence it ranges northward into British America, covering thousands of square miles of the prairie country between Manitoba and the Rocky Mountains, and extending westwards even as far as Queen Charlotte Islands, where it is well developed. It has a prodigious northward extension, for it has been detected in Arctic America near the mouth of the Mackenzie River, and in northern Greenland.

Towards the south over the site of Texas, the Cretaceous sea appears to have been deeper and clearer than elsewhere in the American region, for

[1] Coquand, *Description géol. et paléontol. de la région sud de la Province de Constantin*, 1862; Rolland, *Bull. Soc. Géol. France*, 3e sér. ix. 508.

[2] Medlicott and Blanford, *Geology of India*, see *ante*, p. 258.

its presence is recorded chiefly by limestones, among which occur abundant hippurites (*Caprotina*, *Caprina*) and foraminifera (*Orbitolina*). Northwards the strata are chiefly sandy, and present alternations of marine and terrestrial conditions, pointing to oscillations which especially affected the Rocky Mountain and western regions. The greatest development of the system is to be seen in the north of Utah and in Wyoming, where it presents a continuous series of deposits unbroken by any unconformability for a thickness of from 11,000 to 13,000 feet. The following table shows the character of these deposits in descending order:

Laramie (Lignitic) group.—Buff and grey sandstones, with bands of dark clays and numerous coal-seams, containing abundant terrestrial vegetation of Tertiary types, marine and brackish-water molluscs (*Ammonites lobatus*, *Inoceramus problematicus*, *Ostrea congesta*, *Cyrena Carltoni*, *Physa*, *Valvata*, &c.), and remains of fishes (*Beryx*, *Lepidotus*), turtles (*Trionyx*, *Emys*, *Compsemys*), and reptiles (*Crocodilus*, *Agathaumas*, &c.). This group is by some geologists placed in the Tertiary series, or as a passage series between the Cretaceous and Eocene systems (see below). Thickness in Green River basin 5000 feet.

Fox Hills group.—Grey, rusty, and buff sandstones, with numerous beds of coal and interstratifications of strata containing marine shells (*Belemnitella*, *Nautilus*, *Ammonites*, *Baculites*, *Mosasaurus*, &c.). Thickness on the great plains 1500 feet, which in the Green River basin expands to 3000 to 4000 feet.

Colorado group.—Calcareous shales and clays with a central sandy series, and in the Wahsatch region, seams of coal as well as fluviatile and marine shells. Thickness east of the Rocky Mountains 800 to 1000 feet, but westwards in the region of the Uinta and Wahsatch Mountains . . . 2000 feet.

This group has been proposed and named by Dr. Hayden and Mr. Clarence King to include the following sub-groups in the original classification of Messrs. Meek and Hayden in the Missouri region:

Fort Pierre sub-group.—Carbonaceous shales, marls, and clays (*Inoceramus Barabini*, *Baculites ovatus*, *Scaphites nodosus*, *Ammonites*, *Ostrea congesta*, &c.).

Niobrara sub-group.—Chalky marls and bituminous limestones (*Baculites*, *Inoceramus deformis*, *I. problematicus*, *Ostrea congesta*, fish remains).

Fort Benton sub-group.—Shales, clays, and limestones (*Scaphites warrenensis*, *Ammonites*, *Prionocyclas Woolgari*, *Ostrea congesta*).

Dakotah Group, composed of a persistent basal conglomerate (which is 200 feet thick and very coarse in the Wahsatch region) overlaid by yellow and grey massive sandstones, sometimes with clays and seams of coal or lignite (Dicotyledonous leaves in great numbers, *Inoceramus*, *Cardium*, &c.). Thickness 400 feet and upwards.[1]

The extraordinary palæontological richness of these western Cretaceous deposits has been already referred to. They contain the earliest dicotyledonous plants yet found on this continent, upwards of 100 species having been named, of which one-half were allied to living American forms. Among them are species of oak, willow, poplar, beech, elm, dogwood, maple, hickory, fig, cinnamon, laurel, smilax, tulip-tree, sassafras, sequoia, American palm (*Sabal*), and cycads. The more characteristic mollusca are species of *Terebratula*, *Ostrea*, *Gryphæa*, *Exogyra*, *Inoceramus*, *Hippurites*, *Radiolites*, *Ammonites*, *Scaphites*, *Hamites*, *Baculites*, *Belemnites*, *Ancyloceras*, and *Turrilites*. Of the fishes of the Cretaceous sea many species are known, comprising large predaceous representatives of modern or osseous types like the salmon and saury, though cestracionts and ganoids still flourished. But the most remarkable feature in the organic contents of these beds is the extraordinary number

[1] Hayden's *Reports of Geographical and Geological Surveys of Western Territories*; King's *Geological Report of Exploration of 40th parallel*, vol. i.

and variety of the reptilian remains, to which reference has been already made (p. 810, 811). Some of the earliest types of birds also have been obtained from the same important strata.

No question in American geology has in recent years given rise to more controversy than the place which should be assigned to the Laramie or Lignitic group, whether in the Cretaceous or Tertiary series. The group consists mainly of lacustrine strata, with occasional brackish-water and marine bands. While the mollusca in some of the shell-bearing beds comprise species of *Inoceramus*, *Anchura*, *Gyrodes*, *Cardium*, *Cyrena*, *Melampus*, *Ostrea*, and *Anomia*, in others they belong to the modern lacustrine and fluviatile genera *Physa*, *Valvata*, *Cyrena*, *Corbula*, *Unio*. The abundant terrestrial flora resembles in many respects the present flora of North America. A few of the plants are common to the Middle Tertiary flora of Europe, and a number of them have been met with in the Tertiary beds of the Arctic regions. Some of the seams of vegetable matter are true bituminous coals and even anthracites. According to Cope, the vertebrate remains of the Laramie group bind it indissolubly to the Mesozoic formations. Lesquereux, on the other hand, insists that the vegetation is unequivocally Tertiary. The former opinion has been maintained by Clarence King, Marsh, and others; the latter by Hayden and his associates in the Survey of the Western Territories. Cope, admitting the force of the evidence furnished by the fossil plants, concludes that "there is no alternative but to accept the result that a Tertiary flora was contemporaneous with a Cretaceous fauna, establishing an uninterrupted succession of life across what is generally regarded as one of the greatest breaks in geologic time." The vegetation had apparently advanced more than the fauna in its progress towards modern types. The Laramie group was disturbed along the Rocky Mountain region before the deposition of the succeeding Tertiary formations, for these lie unconformably upon it. So great have been the changes in some regions that the strata have assumed the character of hard slates like those of Palæozoic date, if indeed they have not become in California thoroughly crystalline masses.

The blending of marine and terrestrial formations, so conspicuous in the western Territories of the American Union, can be traced northwards into British America, Vancouver's Island, and the remote Queen Charlotte group, with no diminution in the thickness of the series of strata. The section at Skidegate Inlet in the latter islands is as follows:[1]

Upper shales and sandstones. (Few fossils, the only form recognized being *Inoceramus problematicus*.)	1500 feet
Conglomerates and sandstones (fragments of *Belemnites*). . . .	2000 „
Lower shales and sandstones with a workable seam of anthracite at the base (fossils abundant, including species of *Ammonites*, *Hamites*, *Belemnites*, *Trigonia*, *Inoceramus*, *Ostrea*, *Unio*, *Terebratula*, &c.).	5000 „
Volcanic agglomerates, sandstones, and tuffs, with blocks sometimes four or five feet in diameter	3500 „
Lower sandstones, some tuffaceous, others fossiliferous . . .	1000 „
	13,000 „

[1] G. M. Dawson in *Report of Progress of Geol. Surv. Canada*, 1878-9; J. F. Whiteaves, *Mesozoic Fossils*, vol. i. part i. in publications of *Geol. Survey, Canada*. See also Mr. Dawson's *Report on Geology and Resources of the Region near the 49th parallel; North British Boundary Commission*, 1878; *Report on Canadian Pacific Railway*, Ottawa, 1880.

Southwards, also, the same mingled marine and terrestrial type of Cretaceous rocks can be followed into California, where the higher parts of the series contain beds of coal. The coast ranges are described by Whitney as largely composed of Cretaceous rocks, usually somewhat metamorphic and sometimes highly so.

Australia and New Zealand.—Representatives of the Cretaceous system occupy a vast area in Queensland and in other parts of Australia. Among their fossils are species of *Inoceramus*, *Ammonites*, and *Belemnitella*. In New Zealand the "Waipara" formation of Canterbury is believed to represent Upper Cretaceous and possibly some of the other Tertiary horizons. It consists of massive conglomerates (sometimes 6000 to 8000 feet thick), sandstones, shales, brown-coal seams, and ironstones. The plants include dicotyledonous leaves, cones, and branches of araucarians and leaves and twigs of *Dammara*. Among the shells no cephalopods nor any of the wide-spread hippurites have yet been found. With the remains of fishes (*Lamna*, *Hybodus*, *Otodus*) occur numerous saurian bones, which have been referred to species of *Plesiosaurus*, *Manisaurus*, *Polycotylus*, &c.[1]

[1] Etheridge, *Q. J. Geol. Soc.* xxviii. 183, 340; Owen, *Geol. Mag.* vii. 49; Hector, *Trans. New Zealand Inst.* vi. p. 333; Haast, *Geology of Canterbury and Westland*, p. 291; Hutton and Ulrich, *Geology of Otago*, p. 44.

PART IV.—CAINOZOIC OR TERTIARY.

The close of the Mesozoic periods was marked in the west of Europe by great geographical changes, during which the floor of the Cretaceous sea was raised partly into land and partly into shallow marine and estuarine waters. These events must have occupied a vast period, so that when sedimentation once more became continuous in the region, the organic remains of Mesozoic time had (save in a few low forms of life) entirely disappeared and given place to others of a distinctly more modern type. In England, the interval between the Cretaceous and the next geological period represented there by sedimentary formations is marked by the abrupt line which separates the top of the Chalk from all later accumulations, and by the evidence that the Chalk seems to have been in some places extensively denuded before even the oldest of what are called the Tertiary beds were deposited upon its surface. There is evidently here a considerable gap in the geological record. We have no data for ascertaining what was the general march of events in the south of England between the eras chronicled respectively by the Upper Chalk and the overlying Thanet beds. So marked is this hiatus that the belief was long prevalent that between the records of Mesozoic and Cainozoic time there comes one of the great breaks in the geological history of the globe.

Here and there, however, in the continental part of the Anglo-Parisian basin traces of some of the missing evidence are obtainable. Thus, the Maestricht (Danian, p. 827) shelly and polyzoan limestones, with a conglomeratic base, contain a mingling of true Cretaceous organisms with others which are characteristic of the older Tertiary formations. The common Upper Chalk crinoid, ***Bourgueticrinus ellipticus***, occurs there in great numbers; also ***Ostrea vesicularis, Baculites Faujasii, Belemnitella mucronata***, and the great reptile ***Mosasaurus;*** but associated with such Tertiary genera as ***Voluta, Fasciolaria***, and others. At Faxoe, on the Danish island of Seeland, the uppermost member of the Cretaceous series contains in like manner a blending of well-known Upper Chalk organisms with the Tertiary genera ***Cypræa, Oliva***, and ***Mitra***. In the neighbourhood of Paris also, and in scattered patches over the north of France, the Pisolitic limestone, formerly classed as Tertiary, has been found to include so many distinctively Upper Cretaceous forms as to lead to it being relegated to the top of the Cretaceous series, from which, however, it is marked off by the decided unconformability already described. These fragmentary deposits are interesting, in so far as they help to show that, though in western Europe there is a tolerably abrupt separation between Cretaceous and Tertiary deposits, there was nevertheless no real break between

the two periods. The one merged insensibly into the other; but the strata which would have served as the chronicles of the intervening ages have either never been deposited or have since been in great measure destroyed. In southern Europe, and especially in the south-eastern Alps, no sharp line can be drawn between Cretaceous and Eocene rocks. These deposits merge into each other in such a way as to show that the geographical changes of the western region did not extend into the south and south-east.

The name Tertiary, given in the early days of geology before much was known regarding fossils and their history, has retained its hold on the literature of the science. It is often replaced by the term Cainozoic (*recent life*), which expresses the great fact that it is in the series of strata comprised under this designation that most recent species and genera have their earliest representatives. Taking as the basis of classification the percentage of living species of mollusca found by Deshayes in the different groups of the Tertiary series, Lyell proposed a scheme of arrangement which has been generally adopted. The older Tertiary formations, in which the number of still living species of shells is very small, he named ***Eocene*** (*dawn of the recent*), including under that title those parts of the Tertiary series of the London and Paris basins wherein the proportion of existing species of shells was only 3½ per cent. The middle Tertiary beds in the valleys of the Loire, Garonne, and Dordogne, containing 17 per cent. of living species, were termed ***Miocene*** (*less recent*), that is, containing a minority of recent forms. The younger Tertiary formations of Italy were included under the designation ***Pliocene*** (*more recent*), because they contained a majority, or from 36 to 95 per cent., of living species. This newest series, however, was further subdivided into Older Pliocene (35 to 50 per cent. of living species) and Newer Pliocene (90 to 95 per cent.). A still later group of deposits was termed ***Pleistocene*** (*most recent*), where the shells all belonged to living species, but the mammals were partly extinct forms. This classification, though somewhat artificial, has, with various modifications and amplifications, been adopted for the Tertiary groups, not of Europe only, but of the whole globe. The original percentages, however, often depending on local accidents, have not been very strictly adhered to. The most important modification of the terminology in Europe has been the insertion of another stage or group termed ***Oligocene***, proposed by Beyrich, to include beds that were formerly classed partly as Upper Eocene and partly as Lower Miocene.

Some writers, recognizing a broad distinction between older and younger Tertiary deposits, have proposed a classification into two main groups: 1st, Eocene, Older Tertiary or Palæogene, including Eocene and Oligocene; and 2nd, Younger Tertiary or Neogene. This subdivision has been advocated on the ground that while the older deposits indicate a tropical climate and contain only a very few living species of organisms, the younger groups point to a climate

approaching more and more to that of the existing Mediterranean basin, while the majority of their fossils belong to living species.[1]

The Tertiary periods witnessed the development of the present distribution of land and sea and the upheaval of most of the great mountain chains of the globe. Some of the most colossal disturbances of the terrestrial crust of which any record remains took place during these periods. Not only was the floor of the Cretaceous sea upraised into low lands, with lagoons, estuaries, and lakes, but throughout the heart of the Old World, from the Pyrenees to Japan, the bed of the early Tertiary or nummulitic sea was upheaved into a succession of giant mountains, some portions of that sea-floor now standing at a height of at least 16,500 feet above the sea. The rocks deposited during these periods are distinguished from those of earlier times by increasingly local characters. The nummulitic limestone of the older Tertiary groups is indeed the only wide-spread massive formation which in the uniformity of its lithological and palæontological characters rivals the rocks of Mesozoic and Palæozoic time. As a rule Tertiary deposits are loose and incoherent, and present such local variations, alike in their mineral composition and organic contents, as to show that they were mainly accumulated in detached basins of comparatively limited extent and in seas so shallow as to be apt from time to time to be filled up or elevated and to become in consequence brackish or even fresh. These local characters are increasingly developed in proportion to the recentness of the deposits.

The climate of the Tertiary periods underwent in the northern hemisphere a remarkable change. At the beginning it was of a tropical and subtropical character, even in the centre of Europe and North America. It then gradually became more temperate, but flowering plants and shrubs continued to live even far within the Arctic circle, where, then as now, there must have been six sunless months every year. Growing still milder the climate passed eventually into a phase of extreme cold, when snow and ice extended from the Arctic regions into the centre of Europe and North America. Since that time the cold has again diminished until the present thermal distribution has been reached.

With such changes of geography and of climate, the life of Tertiary time, as might have been anticipated, is found to have been remarkably varied. In entering upon the Tertiary series of formations, we find ourselves upon the threshold of the modern type of life. The ages of lycopods, ferns, cycads, and yew-like conifers have passed away, and that of the dicotyledonous angiosperms—the hard-wood trees and evergreens of to-day—now succeeds them, but not by any sudden extinction and re-creation; for, as we have seen (p. 803), some of these trees had already begun to make their appearance even in Cretaceous times. The hippurites, inocerami, ammonites, belemnites, baculites, turrilites, scaphites, and other molluscs, which had played so large a part in the molluscan life of the

[1] Hörnes, *Jahrb. Geol. Reichsanst.* 1864, p. 510.

later Secondary periods, now cease. The great reptiles, too, which in such wonderful variety of type were the dominant animals of the earth's surface, alike on land and sea, ever since the commencement of the Lias, now wane before the increase of the mammalia, which advance in augmenting diversity of type until they reach a maximum in variety of form and in bulk just before the cold epoch referred to. When that refrigeration passed away and the climate became milder, the extraordinary development of mammalian life that preceded it is found to have disappeared also, being only feebly represented in the living fauna at the head of which man has taken his place.

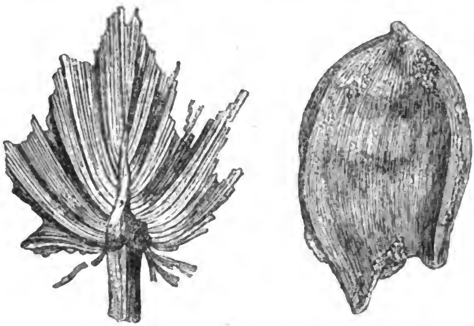
Section I.—Eocene.

§ 1. General Characters.

Rocks.—In the Old World the most widely distributed deposit of this epoch is the nummulitic limestone, which extends from the Pyrenees through the Alps, Carpathians, Caucasus, Asia Minor, Northern Africa, Persia, Beloochistan, and the Suleiman Mountains, and is found in China and Japan. It attains a thickness of several thousand feet. In some places it is composed mainly of foraminifera (*Nummulites* and other genera); but it sometimes includes a tolerably abundant marine fauna. Here and there it has assumed a compact crystalline marble-like structure, and can then hardly be distinguished from a Mesozoic or even Palæozoic rock. Enormous masses of sandstone occur in the Eastern Alps (Vienna sandstone, Flysch), referred partly to the same age, but seldom containing any fossils save fucoids (p. 830). The most familiar European type of Eocene deposits, however, is that of the Anglo-Parisian and Franco-Belgian area, where are found numerous thin local beds of usually soft and uncompacted clay, marl, sand, and sandstone, with hard and soft bands of limestone, containing alternations of marine, brackish, and fresh-water strata.

Life.—The flora of Eocene time has been abundantly preserved on certain horizons. In the English Eocene groups a succession of several distinct floras has been observed, those of the London clay and Bagshot beds being particularly rich. The plants from the London clay indicate a warm climate. They include species of palms (*Sabal, Nipadites*, Fig. 400) and proteaceous plants allied to the living Australian *Petrophila* and *Isopogon;* likewise species of custard-apple, gourd, melon, almond, oak, walnut, *Salisburia, Liquidambar, Magnolia, Eucalyptus, Bankinia.* The remarkable occurrence of Australian types in the Lower Eocene vegetation is observable also in that of the middle Eocene period, when proteaceous plants mingled in the umbrageous forests of evergreen trees —laurels, cypresses, and yews. Among the woodlands there grew species of ferns (*Lygodium, Asplenium*, &c.), also of many of our familiar trees besides those just mentioned, such as chestnuts, beeches, elms,

poplars, hornbeams, willows, figs, planes, and maples. The markedly tropical climate was shown by clumps of Pandanus, with here and there a fan-palm or feather-palm, a tall aroid or a towering cactus. The Australian aspect of the vegetation eventually gave way to



a *b*

FIG. 400.—EOCENE PLANTS.
a, Sabal oxyrhachis (Heer) (reduced); *b*, Nipadites umbonatus (Bow.) (½).

one of a more American character, the Australian *Proteaceæ* being replaced by the American *Myricaceæ*.[1]

The Eocene **fauna** presents similar evidence of tropical or subtropical conditions in central Europe. Especially characteristic are foraminifera of the genus *Nummulites*, which occur in prodigious numbers in the nummulite limestone (Fig. 401), and also occupy

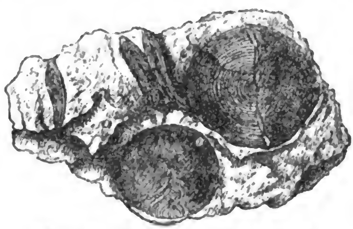


FIG. 401.—NUMMULITIC LIMESTONE (⅓).

different horizons in the English and French Eocene basins. The assemblage of mollusca is very large, most of the genera being still living, though many of them are confined to the warmer seas of the

[1] J. S. Gardner, British Eocene Flora, *Palæontograph. Soc.* 1879. L. Crié, Recherches sur la végétation de l'ouest de la France à l'époque tertiaire. *Ann. Sciences Géol.* ix. (1877).

globe. Characteristic forms are *Belosepia, Nautilus, Cancellaria, Fusus, Pseudoliva, Oliva, Voluta, Conus, Mitra, Cerithium, Melania, Turritella, Rostellaria, Pleurotoma, Cypræa, Natica, Scalaria, Corbula, Cyrena, Cytherea, Chama, Lucina.* Fish remains are not infrequent in some of the clays, chiefly as scattered teeth (Fig. 404). Some of the more common genera are *Lamna, Otodus, Myliobates, Pristis, Phyllodus, Aetobates.* The Eocene reptiles present a singular contrast to those of Mesozoic time. They consist largely of tortoises and turtles, with crocodiles and sea-snakes. An interesting series of remains of birds has been obtained from the English Eocene beds. These include *Argillornis longipennis* (perhaps representative of, but larger than, the modern albatross), *Dasornis londinensis* (somewhat akin to the extinct *Dinornis* of New Zealand), *Enaliornis, Halcyornis toliapicus, Lithornis vulturinus, Macrornis tanaupus, Odontopteryx toliapicus* (a toothed, fish-eating bird with affinities to the pterosaurians).

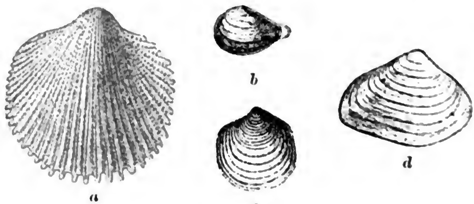


Fig. 402.—Eocene Lamellibranchs.

a, Cardium porulosum (Lam.); *b*, Corbula regulbiensis (Mor.); *c*, Lucina squamula (Desh.); *d*, Cyrena cuneiformis (Sow.) (⅔).

From the upper Eocene beds of the Paris basin ten species of birds have been obtained, including forms allied to the buzzard, woodcock, quail, pelican, ibis, flamingo, and African hornbill.[1] But the most notable feature in the palæontology of the period is the advent of some of the numerous mammalian forms for which Tertiary time was so distinguished. In the lower Eocene period appeared the *Arctocyon* and *Palæonictis,* two animals with marsupial affinities, the former with bear-like teeth, the latter with teeth like those of the Tasmanian dasyure; also the tapir-like *Coryphodon;* the small hog-like *Hyracotherium* with canine teeth like those of the peccary, and a form intermediate between that of the hog and the hyrax; and the allied genus *Pliolophus.* Middle Eocene time was distinguished by the advent of a group of remarkable tapir-like animals (*Palæotherium, Palaplotherium, Lophiodon, Pachynolophus*); true carnivores (*Pterodon* and *Proviverra*); forms allied to hogs and carnivores (*Heterohyus,* &c.); and the lemuroid *Cænopithecus,* the earliest representative

[1] Owen, *Q. J. Geol. Soc.* 1856, 1873, 1878, 1880. Boyd Dawkins, *Early Man in Britain*, p. 33. Milne Edwards, *Oiseaux Fossiles*, ii. 543.

of the tribe of monkeys. With the upper Eocene period, besides the abundant older tapir-like forms, there came others (*Anchitherium*), which presented characters intermediate between those of the tapiroid Palæotheres and the true Equidæ. They were about the size of small ponies, had three toes on each foot, and are regarded as ancestors of the horse. Numerous hog-like animals (*Microchærus, Diplopus, Hyopotamus*) mingled with herds of ancestral

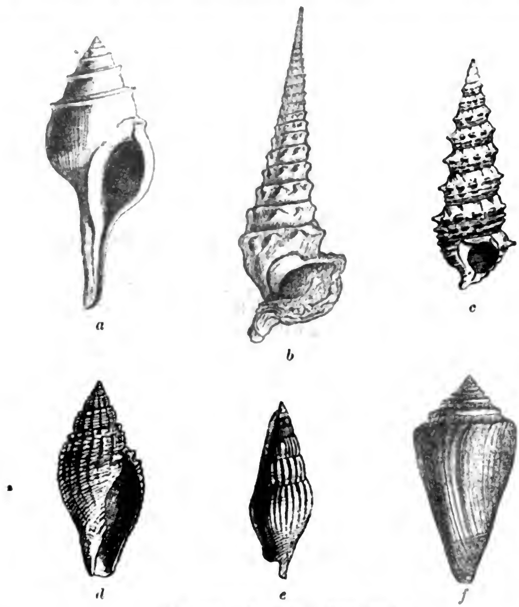


FIG. 403.—EOCENE GASTEROPODS.

a, Fusus longævus (Brand.) ($\frac{2}{3}$); *b*, Cerithium giganteum (Desh.) ($\frac{1}{10}$); *c*, Melania inquinata (Sow.) ($\frac{2}{3}$); *d*, Voluta elevata (Sow.) ($\frac{2}{3}$); *e*, Rostellaria fissurella (Desh.) ($\frac{2}{3}$); *f*, Conus deperditus (Brug.) ($\frac{1}{2}$).

hornless forms of deer and antelopes (*Dichobune, Dichodon, Amphitragulus*). Opossums abounded. Among the carnivores were animals resembling wolves (*Cynodon*), foxes (*Amphicyon*), and wolverines (*Tylodon*), but all possessing marsupial affinities. There appear to have been also representatives of our hedge-hogs, squirrels, and bats.[1]

[1] Gaudry, *Les Enchainements du Monde Animal*, p. 4. Boyd Dawkins, *Early Man in Britain*, chap. ii.

It is from the thick Eocene lacustrine formations of the western Territories of the United States that the most important additions to our knowledge of the animals of early Tertiary time have recently been made, thanks to the admirable and untiring labours first of Leidy, and subsequently of Marsh at Newhaven, and Cope at

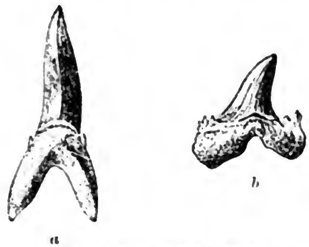


FIG. 404.—EOCENE FISHES.
a, Lamna elegans (Ag.) tooth of ($\frac{1}{1}$); *b*, Otodus obliquus (Ag.), tooth of ($\frac{1}{1}$).

Philadelphia. The herbivorous ungulata appear to have formed a chief element in that western fauna. They included some of the oldest known ancestors of the horse, with four-toed feet, and even in one form (*Eohippus*) with rudiments of a fifth toe; also various hog-like animals (*Eohyus, Parahyus*). Some of the most peculiar forms were

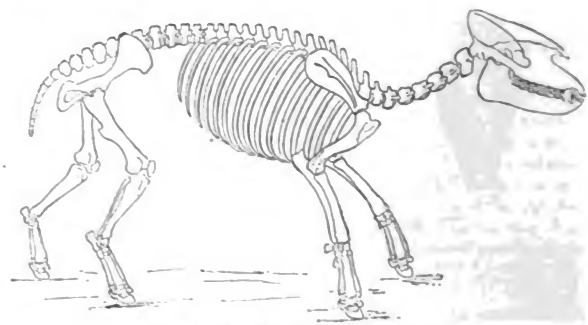


FIG. 405.—PALÆOTHERIUM MAGNUM (CUV.).

those of the type termed Tillodont by Marsh, armed with a pair of long incisors; and the Deinocerata—an extraordinary group possessing according to Marsh the size of elephants, the habits of rhinoceroses, but bearing a pair of long horn-like prominences on the snout, another pair on the forehead, and a single one on each cheek (Fig. 406).

With these animals there coexisted large and small carnivores and some lemuroid monkeys.[1]

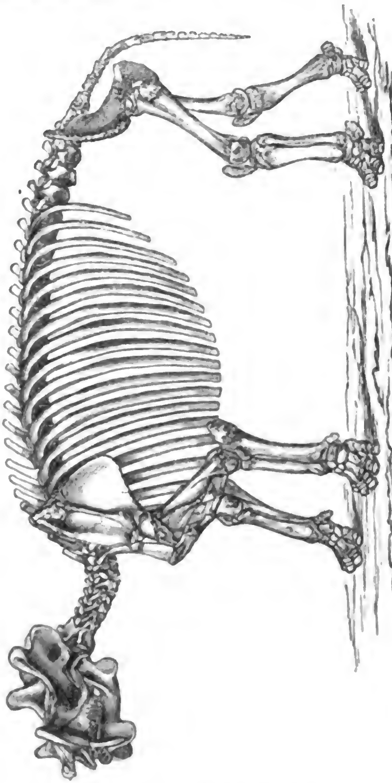


FIG. 406.—DEINOCERAS (MARSH) ($\frac{1}{30}$). RESTORATION OF SKELETON BY PROFESSOR MARSH.

§ 2. Local Development.

Great Britain.[2]—Entirely confined to the south-eastern part of England, the British Eocene strata occupy two synclinal depressions in

[1] The restoration of *Deinoceras* in Fig. 406 has been kindly supplied by Professor Marsh.

[2] See Conybeare and Phillips, *Geology of England and Wales;* Prestwich, *Q. J. Geol. Soc.* vols. iii., vi., viii., x., xi., xiii.; Edward Forbes, "Tertiary Fluvio-marine Formation of the Isle of Wight," *Mem. Geol. Surv.* 1856; H. W. Bristow, "Geology of the Isle of Wight," *Mem. Geol. Surv.* 1862; Whitaker, "Geology of London Basin" in

the Chalk, which, owing to denudation, have become detached into the two well-defined basins of London and Hampshire. They have been arranged as in the subjoined table:

	Hampshire.	*London.*
Upper.	Barton clay.	Upper Bagshot sands.
Middle.	Bracklesham beds, and leaf beds of Bournemouth and Alum Bay.	Middle Bagshot beds, part of Lower Bagshot sands.
Lower.	London clay (Bognor beds). Woolwich and Reading beds.	Part of Lower Bagshot sands. London clay. Oldhaven beds. Woolwich and Reading beds. Thanet beds.

Lower.—The Thanet Beds[1] at the base of the London basin consist of pale yellow and greenish sand, sometimes clayey, and containing at their bottom a thin, but remarkably constant, layer of green-coated flints resting directly on the Chalk. According to Mr. Whitaker, it is doubtful if proof of actual erosion of the chalk can anywhere be seen under the Tertiary deposits in England, and he states that the Thanet Sands everywhere lie upon an even surface of chalk with no visible unconformability.[2] Professor Phillips, on the other hand, describes the chalk at Reading as having been "literally ground down to a plane or undulated surface, as it is this day on some parts of the Yorkshire coast," and having likewise been abundantly bored by lithodomous shells.[3] The Thanet Sands appear to have been formed only in the London basin; at least they have not been recognized at the base of the Eocene series in Hampshire. Their fossils comprise about 70 known species (all marine except a few fragments of terrestrial vegetation). Among them are several foraminifera, numerous lamellibranchs (*Astarte tenera*, *Cyprina planata*, *Ostrea bellovacina*, *Cucullæa decussata* (*crassatina*), *Pholadomya cuneata*, *P. Konincki*, *Corbula regulbiensis*, &c.), a few species of gasteropods (*Natica subdepressa*, *Aporrhais Sowerbii*, &c.), a nautilus, and the teeth, scales, and bones of fishes (*Lamna*, *Pisodus*).

The Woolwich and Reading Beds,[4] or "Plastic Clay" of the older geologists, consist of lenticular sheets of plastic clay, loam, sand, and pebble-beds, so variable in character and thickness over the Tertiary districts that their homotaxial relations would not at first be suspected. One type, presenting unfossiliferous lenticular, mottled, bright-coloured clays, with sands, sometimes gravels, and even sandstones and conglomerates, occurs throughout the Hampshire basin and in the northern and western part of the London basin. A second type, found in West Kent, Surrey, &c., consists of light-coloured sands and grey clays, crowded with estuarial shells. A third type, seen in East Kent, is composed only of sands containing marine fossils. These differ-

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Mem. Geol. Surv. vol. iv. (1872); Phillips, *Geology of Oxford and the Thames Valley*, 1871.

[1] Prestwich, *Q. J. Geol. Soc.* viii. (1852), p. 237.

[2] "Geology of London," *Mem. Geol. Surv.* iv. p. 57.

[3] *Geology of Oxford*, p. 442.

[4] Prestwich, *Q. J. Geol. Soc.* x. p. 75. Whitaker, *Geol. Lond.* p. 98.

ences in lithological and palæontological characters serve to indicate the geographical features of the south-east of England at the time of deposit, showing in particular that the sea of the Thanet Beds had gradually shallowed, and that an estuary now partly extended over its site. The organic remains as yet obtained from this group amount to more than 100 species. They include a few plants of terrestrial growth, such as *Ficus Forbesi*, *Grevillea Heeri*, and *Laurus Hookeri*—a flora which, containing some apparently persistent types, has a temperate facies.[1] The lamellibranchs are partly estuarine or fresh-water, partly marine; characteristic species being *Cyrena cuneiformis* and *C. tellinella*. *Ostrea bellovacina* forms a thick oyster-bed at the base of the series. *Ostrea tenera* is likewise abundant. The gasteropods include a similar mixture of marine with fluviatile species (*Cerithium funatum* (*variabile*), *Melania inquinata*, *Melanopsis buccinoides*, *Neritina globulus*, *Natica subdepressa*, *Fusus latus*, *Paludina lenta*, *Pitharella Rickmanni*, &c.). The fish are chiefly sharks (*Lamna*). Bones of turtles, scutes of crocodiles, and traces of birds have been found. The highest organisms are bones of mammalia, including the *Coryphodon*.

The Oldhaven Beds,[2] forming the base of the London Clay, consist almost wholly of rolled flint pebbles in a sandy base, which, as Mr. Whitaker suggests, may have accumulated as a bank some little distance from shore. Though of trifling thickness (20 to 30 feet) they have yielded upwards of 150 species of fossils. Traces of *Ficus*, *Cinnamomum*, and *Coniferæ* have been obtained from them, indicating perhaps a more subtropical character than the flora of the beds below, but without the Australian and American types which appear in so marked a manner in the later Eocene floras.[3] The organisms, however, are chiefly marine and partly estuarine shells, the gasteropods being particularly abundant.

The London Clay[4] is a deposit of stiff brown and bluish-grey clay, with layers of septarian nodules of argillaceous limestone. Its bottom beds, commonly consisting of green and yellow sands, and rounded flint-pebbles, sometimes bound by a calcareous cement into hard tabular masses, form in the London basin a well-marked horizon. The London Clay is typically developed in that basin, attaining its maximum thickness (500 feet) in the south of Essex. Its representative in the Hampshire basin is known as the "Bognor Beds," but these strata differ somewhat both lithologically and palæontologically from the typical development. The London Clay has yielded a long and varied suite of organic remains, from which we can see that it must have been laid down in the sea beyond the mouth of a large estuary, into which abundant relics of the vegetation, and even sometimes of the fauna of the adjacent land, were swept. According to Prof. T. Rupert Jones the depth of the sea, as indicated by the foraminifera of the deposit, may have been about 600 feet. Professor Prestwich has pointed out that there are traces of the existence of palæontological zones in the clay, the lowest zone indicating in the east of the area of deposit a maximum depth of water, while a progressive shallowing is shown by three higher

[1] J. S. Gardner, "British Eocene Flora," *Palæontog. Soc.* p. 29.
[2] Whitaker, *Q. J. Geol. Soc.* xxii. (1866), p. 412; *Geology of London*, p. 239.
[3] J. S. Gardner, *Op. cit.* pp. 2, 10.
[4] Prestwich, *Q. J. Geol. Soc.* vi. p. 255; x. p. 435. Whitaker, *Geology of London*, p. 273.

zones, the uppermost of which contains the greater part of the terrestrial vegetation, and also most of the fish and reptilian remains. The fossils are mainly marine mollusca, which, taken in connection with the flora, indicate that the climate was somewhat tropical in character. The plants include the fruits or seeds of the following, among other genera: *Pinus*, *Callitris*, *Salisburia*; *Musa*, *Sabal*, *Elais*, *Nipadites*, *Iriartea*, *Livistona*, *Œnocarpus*; *Quercus*, *Liquidambar*, *Nyssa*, *Diospyros*, *Symplocos*, *Magnolia*, *Juglans*, *Eucalyptus*, *Amygdalus*, *Bankinia*.[1] Crustacea abound (*Xanthopsis*, *Hoploparia*). Gasteropods are the prevalent molluscs, the common genera being *Pleurotoma* (45 species), *Fusus* (15 species), *Cypræa*, *Murex*, *Cassidaria*, *Pyrula*, and *Voluta*. The cephalopods are represented by 6 or more species of *Nautilus*, by *Belosepia sepioidea*, and *Beloptera Levesquei*. Nearly 100 species of fishes occur in this formation, the rays (*Myliobates*, 14 species) and sharks (*Lamna*, *Otodus*, &c.) being specially numerous. A sword-fish (*Tetrapterus priscus*), and a saw-fish (*Pristis bisulcatus*) about 10 feet long, have been described by Agassiz from the London Clay of Sheppey, whence almost the whole of the fish remains have been obtained. The reptiles were numerous, but markedly unlike, as a whole, to those of Secondary times. Among them are numerous turtles and tortoises (*Chelone* 10 species, *Trionyx* 1 species, *Platemys* 6 species), two species of crocodile, and a sea-snake (*Palæophis toliapicus*), estimated to have equalled in size a living *Boa constrictor*. Remains of birds have also been met with (*Lithornis vulturinus*, *Halcyornis toliapicus*, *Dasornis londinensis*, *Odontopteryx toliapicus*, *Argillornis longipennis*, *Enaliornis*). The mammals numbered among their species a hog (*Hyracotherium*), several tapirs (*Coryphodon*, &c.), an opossum (*Didelphys*), and a bat. The carcases of these animals must have been borne seawards by the great river which transported so much of the vegetation of the neighbouring land.

Middle.—In the London basin this division consists chiefly of sands, which are comprised in the two groups of the lower and middle "Bagshot beds." The lower of these two groups, consisting of yellow siliceous, unfossiliferous sands, with irregular light clayey beds, attains a thickness of about 100 to 150 feet. The second group, or "Middle Bagshot beds," is made up of sands and clays, sometimes 50 or 60 feet thick, containing few organic remains, among which are bones of turtles and sharks, with a few molluscs (*Cardita acuticostata*, *C. elegans*, *C. planicosta*, *C. imbricata*, *Corbula gallica*, *C. striata*, *Ostrea flabellula*). In the Hampshire basin the Lower Bagshot beds attain a much greater development, being not less than 660 feet thick in the Isle of Wight, where they consist of variously coloured unfossiliferous sands and clays, with minor beds of ironstone and plant-bearing clays. On the mainland at Studland, Poole, and Bournemouth, the same beds appear. The Middle Bagshot beds are represented in the Hampshire basin by an important series of clays, marls, sands, and lignites upwards of 100 feet thick, known as the Bracklesham beds, from their occurrence at Bracklesham, on the coast of Sussex. From these strata a large series of marine organisms has been obtained, among which are *Belosepia sepioidea*, *B. Cuvieri*, *Cypræa inflata*, *C. tuberculosa*, *Marginella eburnea*, *M. ovulata*, *Voluta crenulata*, *V. spinosa*, *V. angusta*, *V. Branderi*, *V. cythara*, *V. muricina*, *Mitra labratula*, *Conus*

[1] Ettingshausen and Gardner, "British Eocene Flora," *Palæontograph. Soc.* p. 12.

deperditus, C. Lamarckii, Pleurotoma dentata, P. textiliosa, Murex asper, Fusus longævus, Turritella imbricata, Ostrea dorsata, O. flabellula, O. longirostris, Pecten corneus, P. squamula, Lima expansa, Spondylus rarispina, Avicula media, Pinna margaritacea, Modiola Deshayesii, Arca biangula (Branderi), A. interrupta, A. planicosta, Limopsis granulata, Nucula minor, Leda galeottiana, Cardita acuticostata, C. elegans, C. imbricata, C. planicosta, Crassatella grignonensis, Chama calcarata, C. gigas, Nummulites lævigata, N. scabra, Alveolina fusiformis.[1] The Bracklesham beds reappear to a small extent in the London basin, where they form part of the Middle Bagshot beds.

The fossils of the Middle Eocene division occur chiefly in the clays. An abundant terrestrial flora has been obtained from the plant beds of Alum Bay and Bournemouth, the *Proteaceæ* being there still numerous, together with species of fig, cinnamon, fan-palm (*Sabal*), oak, yew, cypress, laurel, lime, senna, and many more.[2] Crocodiles still haunted the waters, for their bones are mingled with those of sea-snakes and turtles, and with tapiroid and other older Tertiary types of terrestrial creatures. The occurrence of the foraminiferal genus *Nummulites* is noteworthy. Though comparatively infrequent in England, it plays, as already stated, an important part in the Eocene deposits of Central and Eastern Europe.

Upper.—The highest division of the Eocene strata of England, according to the classification here followed, includes the uppermost part of the Hampshire series, which has long been known as the "Barton Clay," with, perhaps, the Upper Bagshot sand of the London basin. The Barton clay does not occur in that basin, but forms an important feature in that of Hampshire, where, on the cliffs of Hordwell, Barton, and in the Isle of Wight, it attains a thickness of 300 feet. It consists of grey, greenish, and brown clays, with bands of sand, and has long been well known for the abundance and excellent preservation of its fossils, chiefly molluscs, of which more than 200 species have been collected, but including also fishes (*Lamna, Myliobates*) and a crocodile. The following list includes some of the more important species for purposes of comparison with equivalent foreign deposits: *Voluta luctatrix, V. ambigua, V. athleta, Conus scabriculus, C. dormitor, Pleurotoma rostrata* (and numerous other species), *Fusus longævus, F. pyrus, Ostrea gigantea, Vulsella deperdita, Pecten reconditus, Lima compta, L. soror, Avicula media, Modiola seminuda, M. sulcata, M. tenuistriata, Arca appendiculata, Pectunculus deletus, Cardita Davidsoni, C. sulcata, Crassatella sulcata, Chama squamosa, Nummulites planulata, N. variolaria.*

Northern France and Belgium.—The anticline of the Weald which separates the basins of London and Hampshire is prolonged into the Continent, where it divides the Tertiary areas of Belgium from those of Northern France. There is so much general similarity among the older Tertiary deposits of the whole area traversed by this fold as to indicate a probable original relation as parts of one great tract of sedimentation. Local differences, such as the replacement of fresh-water

[1] See Dixon's *Geology of Sussex;* Edwards and S. Wood, "Monograph of Eocene Mollusca," *Palæontograph. Soc.*

[2] See H. W. Bristow, "Geology of Isle of Wight" in *Mem. Geol. Surv.*; J. S. Gardner, *Geol. Mag.* 1877, p. 129; *Nature*, vol. xxi. (1879), 181, and the Monograph on Eocene flora already cited.

beds in one region by marine beds in another, together with occasional gaps in the record, show us some of the geographical conditions and oscillations during the time of deposition.

Lower.—In the Paris basin the Sables de Bracheux form an excellent horizon, which corresponds to the Thanet sand of England and Dumont's "système landenien" in Belgium. Below this horizon there occurs in the Franco-Belgian region a lower series of deposits than is found in England. In the Paris basin these strata present a variable and local character, but, according to Hébert, may be grouped as under in descending order:

Marl of Dormans (*Physa gigantea*).
Conglomerate of Meudon with fresh-water shells = Marine Heersian marl of Belgium.
Rilly limestone (fresh-water) and strontianiferous marls of Meudon, corresponding to the upper Heersian sands.
Hyaline sands of Rilly, corresponding to the lower part of the hyaline sands of Heers.
Marine conglomerate of Rilly and conglomerates of Nemours (marine fossils), corresponding to the denudation between the Mons limestone and the Heersian beds.
Mons limestone, not represented in Paris basin.[1]

The Sables de Bracheux, traceable as a definite platform through the Anglo-French and Belgian area, contain among their characteristic fossils *Pholadomya cuneata*, *P. Koninckii*, *Cyprina Morrisii*, *Cucullæa crassatina*, *Pecten breveauritus*, *Psammobia Edwardsii*, *Corbula regulbiensis*, *Turritella bellovacina*, *Natica deshayesiana*. The lignites of the Soissonnais are intercalated among beds of sand and clay, containing the same molluscan fauna as the Woolwich and Reading beds. But a break seems to occur in the series at this point; for in the Paris basin no representative of the London Clay is found. The lignites of the Soissonnais are covered by sands (Sables de Cuise) containing, among other abundant marine organisms, *Nummulites planulata*, *Turritella edita*, *T. hybrida*, *Crassatella propinqua*, *Lucina squamula*; they are regarded as the equivalent of the lower part of the English Bagshot sand, and form the highest member of the Lower Eocene of the Paris basin.

In the Belgian area some differences are presented in the succession of sediments. The strata of that district have been grouped by Dumont into a series of "systèmes." The most ancient Tertiary deposit of the west of Europe appears to be the limestone of Mons (Système Montien). This rock lies in a denuded hollow of the Chalk, and has been found by boring to be more than 300 feet thick. It consists of friable and compact limestone, charged with a remarkable series of organic remains. Upwards of 400 species of fossils have been obtained from it, including marine, fresh-water, and terrestrial shells. Among them are about 200 species of gasteropods, about 125 lamellibranchs, and fifty polyzoa, besides numerous foraminifers (*Quinqueloculina*), and calcareous algæ (*Dactylopora*, *Acicularia*, &c.). Two conspicuous features in this deposit are the extraordinary proportion of its new and peculiar species, and the resemblance of its fauna, especially its numerous Cerithiums and Turritellas, to that of the middle Eocene beds of Belgium and the Paris basin rather

[1] Hébert, *Ann. Sciences Géol.* iv. (1873), Art. iv. p. 14.

than to that of the lower Eocene. The Mons limestone has thus been cited as an illustration of Barrande's doctrine of colonies.[1]

Above this deposit comes the "Système Heersien," so named from its development at Heers, in Limbourg. With a total depth of about 100 feet, it consists of (1) a lower division of sandy beds, with *Cyprina planata*, *C. Morrisi*, *Modiola elegans*, and other marine shells, some of which occur in the Thanet sand of England and the Sables de Bracheux; and (2) an upper division of marls, containing, besides some of the marine shells found in the lower division, numerous remains of a terrestrial vegetation (*Osmunda eocenica*, *Chamæcyparis belgica*, *Poacites latissimus*, and species of *Quercus*, *Salix*, *Cinnamomum*, *Laurus*, *Viburnum*, *Hedera*, *Aralia*, &c.).[2]

The "Système Landenien," corresponding to the Thanet and Woolwich and Reading beds of England and the Sables de Bracheux, Argile plastique, and Lignites du Soissonnais of France, is divisible into two stages: 1st, Lower marine gravels, conglomerates, sandstones, marls, &c., with badly preserved fossils, among which are *Turritella bellovacina*, *Cucullæa decussata* (*crassatina*), *Cardium Edwardsi*, *Cyprina planata*, *Corbula regulbiensis*, *Pholadomya Konincki*; 2nd, Upper fluvio-marine sands, sandstones, marls, and lignites containing *Melania inquinata*, *Melanopsis buccinoides*, *Cerithium funatum*, *Ostrea bellovacina*, *Cyrena cuneiformis*, with leaves and stems of terrestrial plants.

The "Système Ypresien" consists of a great series of clays and sands answering generally to the London Clay, but not represented in France. It is divided into two stages: 1st, Lower stiff grey or brown clay, sometimes becoming sandy, and probably an eastward extension of the London Clay. The break between this deposit and the top of the Landenian beds below is regarded as filled up by the Oldhaven beds of the London basin. The only recorded fossils are foraminifera agreeing with those of the London Clay. 2nd, Upper sands with occasional lenticular intercalations of thin greyish-green clays, with abundant fossils, the most frequent of which are *Nummulites planulata* (forming aggregated masses), *Turritella edita*, *T. hybrida*, *Vermetus bognorensis*, *Pecten corneus*, *Pectunculus decussatus*, *Lucina squamula*, *Ditrupa plana*. Out of 72 species of molluscs, 45 are found also in the Sables de Cuise and 20 in the London Clay.[3]

The "Système Paniselien," so named from Mont Panisel near Mons, consists chiefly of sandy deposits not markedly fossiliferous, but containing among other forms, *Rostellaria fissurella*, *Voluta elevata*, *Turritella Dixoni*, *Cytherea ambigua*, *Lucina squamula*. Out of 129 species of mollusca found in this deposit, 91 appear in the Sables de Cuise and only 36 pass up into the Calcaire Grossier. Hence the Paniselian beds are placed at the top of the Lower Eocene stages of Belgium.

Middle.—This division in the Paris basin is formed by the characteristic, prodigiously fossiliferous Calcaire Grossier, which is subdivided as under:[4]

[1] Briart et Cornet, *Mém. Couronn. Acad. Roy. Belg.* xxxvi. (1870); xxxvii. (1873); xliii. (1880). Mourlon, *Geol. Belg.* 1880, p. 192. Hébert (*Ann. Sciences Geol.* iv. 1873, p. 15) has noticed an affinity to the uppermost Cretaceous fauna of Paris.

[2] De Saporta et Marion, *Mém. Cour. Acad. Belg.* xli. (1878).

[3] Mourlon, *Geol. Belg.* p. 211.

[4] Dollfuss, *Bull. Soc. Géol. France.* 3e sér. vi. (1878), p. 269.

Caillasses or Upper Calcaire Grossier.	Upper sub-group with *Cardium obliquum* and *Cerithium denticulatum*.	4. Limestone with *Cardium obliquum* and *Cerithium Blanvilli*.
		3. Limestone with *Cerithium denticulatum* and *C. cristatum*.
		2. Siliceous limestone with undetermined forms of *Potamides*.
		1. Coral limestone (*Stylocœnia*).
	Middle sub-group with *Lucina saxorum* and *Miliola*.	4. Siliceous limestone with parting of laminated marl.
		3. Limestone in small thin boards with *Corbula* (Rochette).
		2. Limestone with *Miliola* and *Lucina saxorum* (Roche).
		1. Siliceous limestone with indeterminate fossils (Bancs francs).
	Lower sub-group with *Cerithium lapidum* and *Miliola*.	4. Limestone (dolomitic) with *Miliola* (Cliquart).
		3. Green marl . . . . . / Siliceous limestone in two beds / Green marl . . . . . — Blanc vert.
		2. Miliola limestone (dolomitic) (Saint Nom).
		1. Siliceous limestone with *Potamides*.
Middle Calcaire Grossier.		5. Limestone with *Lucina concentrica*, *Arca barbatula*, *Cardium aviculare*, *Miliola*, &c.
		4. Limestone with *Orbitolites*, *Fusus bulbiformis*, *Volvaria bulloides*, *Cardium granulosum*, *Arca quadrilatera*, several species of large *Flustra* or *Membranipora*.
		3. Limestone with *Fabularia* and terrestrial vegetation (*Orbitolites complanata*, *Chama calcarata*, *Cardita imbricata*, &c.).
		2. Mass of *Miliola* limestone (*Turritella imbricataria*, *Chama calcarata*, *Lucina mutabilis*, &c.).
		1. Limestone with *Miliola* and *Terebratula* (*T. bisinuata*).
Lower Calcaire Grossier.		5. Glauconitic calcaire grossier with *Cerithium giganteum*.
		4. Glauconitic calcareous sand with *Lenita patellaris*.
		3. Sandy glauconitic calcaire grossier with *Cardium porulosum*.
		2. Sandy glauconitic calcaire grossier, with *Nummulites lævigata*, *N. scabra*, *Ostrea multicostata*, *O. flabellula*, *Ditrupa plana*.
		1. Glauconitic sand, sometimes calcareous and indurated, with pebbles of green quartz, sharks' teeth, and rolled fragments of coral.

In Belgium the middle Eocene presents a different aspect from that of Paris, approximating rather to the English type. It consists of (1) a lower set of sandy beds grouped under the name of "Bruxellian," rich in fossils, which however are usually badly preserved. Among the forms are remains of terrestrial vegetation (*Nipadites Burtini*), also *Paracyathus crassus*, *Maretia grignonensis*, *Pyripora contesta*, *Ostrea cymbula*, *Cardita decussata*, *Chama calcarata*, *Cardium porulosum*, *Cerithium unisulcatum*, *Natica labellata*, *Voluta lineola*, *Ancillaria buccinoides*, *Fusus longævus*, numerous remains of fishes, especially of the genera *Myliobates*, *Otodus*, *Lamna*, *Galeocerdo*, and various reptiles, including species of *Trionyx* and *Chelonia* with *Emys Camperi*, *Gavialis Dixoni*, and *Palæophis typhæus*; (2) a group of sands and fossiliferous calcareous sandstones ("Læke-

nien"), made up of *Ditrupa strangulata* and *Nummulites* (*N. lævigata*, *N. scabra*, *N. Heberti*, *N. variolaria*), and abounding in *Anomia sublævigata*.

Upper.—In the Paris basin this subdivision consists of the following stages:[1]

Gyps Marin.	Gypsum with nodules of silica (menilite), and containing marine fossils (*Cerithium tricarinatum*, *C. pleurotomoides*, *Turritella incerta*).
	Yellow marls with *Lucina inornata*.
	Gypsum, saccharoid and crystallized, with brown marls.
	Yellow, brown, and greenish marls, with *Pholadomya ludensis*, *Crassatella Desmaresti*, &c.
Sables Moyens.	Green sands of Monceaux (*Cerithium Cordieri*, *C. tricarinatum*, *Natica parisiensis*).
	Limestone of Saint Ouen—a marly fresh-water rock 20 to 26 feet thick, composed of two zones, the lower full of *Bythinia*, and the upper abounding in *Limnæa*.
	Sands of Mortefontaine (*Avicula Defrancei*).
	Sands and sandstones of Beauchamp (*Cerithium scalaroides*, *C. Bouei*, *Melania hordacea*, *Cyrena deperdita*, *Planorbis nitidulus*, &c.).
	Sands, &c., with *Nummulites variolaria*, *Ostrea dorsata*, *Cyrena deperdita*, corals, *Lamna elegans*, *Otodus obliquus*, &c.

Northwards in the Belgian area, near Brussels, the highest Eocene strata consist of sands and calcareous sandstones ("Wemmelien"), separated from the similar Lækenian beds below by a gravel full of *Nummulites variolaria*. Other common fossils are *Turbinolia sulcata*, *Corbula pisum*, *Cardita sulcata*, *Turritella brevis*, *Fusus longævus*.

Southern Europe.—The contrast between the facies of the Cretaceous system in north-western and in southern Europe is repeated with even greater distinctness in the Eocene series of deposits. From the Pyrenees eastwards, through the Alps and Apennines into Greece and the southern side of the Mediterranean basin, through the Carpathian Mountains and the Balkan into Asia Minor, and thence through Persia and the heart of Asia to the shores of China and Japan, a series of massive limestones has been traced, which, from the abundance of their characteristic foraminifera, have been called the Nummulitic Limestone. Unlike the thin, soft, modern-looking, undisturbed beds of the Anglo-Parisian area, these limestones attain a depth of sometimes several thousand feet of hard, compact, sometimes crystalline rock, passing even into marble, and they have been folded and fractured on such a colossal scale that their strata have been heaved up into lofty mountain crests sometimes 10,000, and in the Himalaya range more than 16,000, feet above the sea. With the limestones is associated the sandy series known as Nummulite sandstone. The massive unfossiliferous Vienna sandstone and Flysch, already referred to as probably in part Cretaceous, may also belong partly to Eocene time. One of the most remarkable features of these Alpine Eocene deposits is the occurrence in them of gigantic erratics of various crystalline rocks. As far east as the neighbourhood of Vienna, and westward at Bolgen near Sonthofen in Bavaria, near Habkeren and in other places, blocks of granite, granitite, and gneiss occur singly or in groups in the Eocene strata. These travelled masses appear to have most petrographical resemblance, not to any Alpine rocks now visible, but to the Archæan masses in southern Bohemia. Their presence seems to indicate the existence of glaciers in the middle of Europe during some

[1] See Dollfuss, *Op. cit.*

part of the Eocene age. One of the most remarkable Eocene deposits of the Alpine region is the coal-bearing group of Häring, in the Northern Tyrol, where a seam of coal occurs which, with its partings, attains a thickness of 32 feet.

The Nummulitic series has been divided into stages in different regions of its distribution, and attempts have been made by means of the included fossils to parallel these stages in a general way with the subdivisions in the Anglo-Parisian basin. But the conditions of deposition were so different that such correlations must always be regarded as only wide approximations to the truth. In the Northern Alps (Bavaria, &c.) Gümbel arranges the Eocene series as under: [1]

Flysch or Vienna sandstone (upper Eocene), including younger Nummulitic beds and Häring beds.

Lower Nummulitic group. Kressenberg beds—greenish sandy strata abounding in fossils, which on the whole point to a correspondence with the Calcaire Grossier.

Burberg beds—greensand with small Nummulites and *Exogyra Brongniarti*, answering possibly to the upper part of the lower Eocene beds of the Anglo-Parisian area.

In the Southern and South-Eastern Alps the Eocene rocks attain a much larger development. The following subdivisions in descending order have been recognized: [2]

Upper Eocene.	Macigno or Tassello, having the usual character of the Vienna sandstone. No fossils but fucoids.
	Fossiliferous calcareous marls and shales, and thick conglomerates.
Nummulite-Limestone.	Chief Nummulite limestone, containing the most abundant and varied development of nummulites, and attaining the thickest mass and widest geographical range.
	Borelis (Alveolina) limestone, containing numerous large foraminifera of the genus *Borelis*.
	Lower Nummulite limestone, with small nummulites, and in many places banks of corals.
Liburnian Stage.	Upper Foraminiferal limestone, containing also intercalations of fresh-water beds (*Chara*).
	Cosina beds, with a peculiar fresh-water fauna (*Stomatopsis*, *Melania*, *Chara*, &c.).
	Lower Foraminiferal limestone, with numerous marine mollusca (*Anomia*, *Cerithium*, &c.), and with occasional beds of fresh-water limestone (*Chara*, *Melania*, &c.).

India, &c.—As above stated the massive Nummulitic limestone extends through the heart of the Old World, and enters largely into the structure of the more important mountain chains. In India a tolerably copious development of Eocene rocks has been observed, but it is not quite certain where their upper limit should be drawn to place them on a parallel with the corresponding groups in Europe. The following subdivisions in descending order are observed in Sind: [3]

Nari group. Sandstones without marine fossils, and probably of fresh-water origin, 4000 to 6000 feet, representing, perhaps, upper Eocene and Oligocene or lower Miocene beds of Europe.

Kasauli and Dagshai groups of sub-Himalayas.

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[1] *Geognostische Beschreib. Bayersch. Alpen*, 1861, p. 593, *et seq.*
[2] Von Hauer, *Geologie*, p. 569.
[3] Medlicott and Blanford's *Geology of India*, chap. xix.

Kirthar group. A marine limestone formation in general, but passing locally into sandstones and shales. The upper limestones contain *Nummulites garansensis*, *N. sublævigata*.

Nummulitic limestone of Sind, Punjab, Assam, Burmah, &c. Subathú of sub-Himalayas, Indus or Shingo beds of Western Thibet.

Ranikot beds—sandstones, shales, clays with gypsum and lignite, 1500 to 2000 feet; abundant marine fauna, including *Nummulites spira*, *N. irregularis*, *N. Leymeriei*.

Lower Nummulitic group of Salt Range.

North America.—Tertiary formations of marine origin extend in a strip of low land along the Atlantic border of the United States, from the coast of New Jersey southward round the margin of the Gulf of Mexico, whence they run up the valley of the Mississippi to beyond the mouth of the Ohio. On the western sea-board they also occur in the coast ranges of California and Oregon, where they sometimes have a thickness of 3000 or 4000 feet, and reach a height of 3000 feet above the sea. Over the Rocky Mountain region Tertiary strata cover an extensive area, but are chiefly of fresh-water origin. The following are the subdivisions into which they have been grouped, together with their supposed European equivalents:

3. Sumter series = Pliocene.
2. Yorktown „ = Miocene, with perhaps part of Pliocene.
1. Alabama „ = Eocene.

Alabama Group.—As the name implies, this group is well developed in the State of Alabama, where it consists of the following two subgroups in ascending order,—(1) the Clayborne beds — clays, marls, limestones, lignite, and sands; and (2) the Vicksburg beds—lignitic clays, limestones, and marls,—the whole attaining a thickness of nearly 250 feet. But the strata thicken into South Carolina. The fossils of the Alabama group in the eastern States comprise numerous sharks, some of which are specifically, and more are generically, the same as some of the English Eocene forms, such as *Lamna elegans* and *Carcharodon megalodon;* also bones of several crocodiles and snakes.

Over the Rocky Mountain region and the vast plateaux lying to the west of that range the older Tertiary beds consist mainly of lacustrine strata of great thickness, wherein the following subdivisions in descending order have been established:

4. Uinta group (400 feet) or "Diplacadon beds."
3. Bridger group (5000 feet) or "Deinoceras beds."
2. Green River group (2000 feet).
1. Wahsatch (Vermilion Creek) group (5000 feet).

The extraordinary richness of these strata in vertebrate and particularly mammalian remains, already referred to (p. 842), has given them a high importance in geological and palæontological history.

Section II.—Oligocene.

§ 1. General Characters.

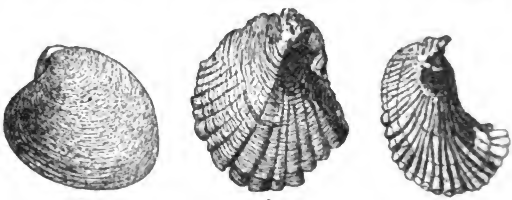
The term "Oligocene" was proposed in 1854 and again in 1858 by Professor Beyrich[1] to include a group of strata distinct from the Eocene beds of France and Belgium, and which Lyell had classed as "Older Miocene." They consist partly of terrestrial, partly of

a b

Fig. 407.—Oligocene Plants.

a, Sequoia Langsdorfii (Brongn.) ($\frac{1}{2}$) (from Heer's *Flor. Tert. Helvetiæ*, i. pl. 21): *b*, Chara Lyellii (Forbes) ($\frac{10}{1}$).

fresh-water and brackish, and partly of marine beds, indicating considerable oscillations of level in the European area. They consequently present none of the massive deeper-water characters so conspicuous in some of the Eocene subdivisions. Among other



a b c

Fig. 408.—Oligocene Lamellibranchs.

a, Cytherea incrassata (Sow.) ($\frac{2}{3}$); *b*, Ostrea cyathula (Lam.) ($\frac{2}{3}$); *c*, Ostrea flabellula (Lam.) ($\frac{2}{3}$).

geographical changes of which they preserve the chronicles is the evidence of the gradual conversion of portions of the sea-floor over the heart of Europe into wide lake-basins in which thick lacustrine

[1] *Monatsbericht, Akad. Berlin*, 1854, pp. 640–666, 1858, p. 51.

deposits were accumulated. Some of these lakes did not attain their fullest development until the Miocene period.

The Oligocene flora according to Heer is composed mainly of an evergreen vegetation and has characters linking it with the living tropical floras of India and Australia and with the subtropical flora of America. It includes some ferns, fan-palms, and feather-palms

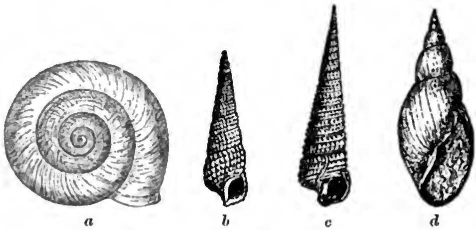


FIG. 409.—OLIGOCENE GASTEROPODS.

a, Planorbis euomphalus (Sow.) ([illegible]); *b*, Cerithium plicatum (Lam.) ([illegible]); *c*, Potamides cinctus (Sow.) ([illegible]); *d*, Limnæa longiscata (Brongn.) ([illegible]).

(*Sabal*, *Phœnicites*), a number of conifers (*Sequoia*, &c.), cinnamon trees, evergreen oaks, custard-apples, gum-trees, spindle-trees, oaks, figs, laurels, willows, vines, and proteaceous shrubs (*Dryandra*, *Dryandroides*).

Among the mollusca some of the more important genera are *Ostrea*, *Pecten*, *Nucula*, *Astarte*, *Cardium*, *Cytherea*, *Cancellaria*,

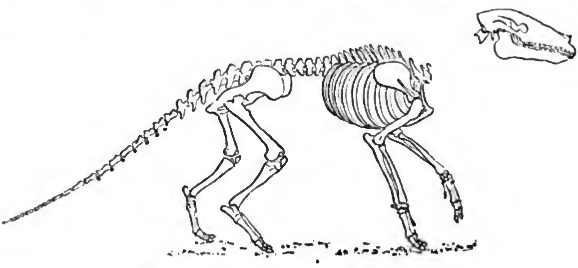


FIG. 410.—ANOPLOTHERIUM COMMUNE (CUV.)

Murex, *Fusus*, *Typhis*, *Cassis*, *Pleurotoma*, *Conus*, *Voluta*, *Cerithium*, *Melania*, *Planorbis*. Numerous remains of birds have been found in the lacustrine beds of the Department of the Allier, no fewer than 66 species having been described, which comprise parroquets, trogons, flamingoes, ibises, pelicans, marabouts, cranes, secretary-birds, eagles, grouse, and numerous gallinaceous birds—a fauna

reminding us of that of the lakes in Southern Africa.[1] The mammalia increase in variety of forms. According to Gaudry the following chronological sequences of appearances and disappearances during the Oligocene period have been noted:[2]

Upper. (St. Gérand-le-Puy (Allier), Calcaire de Beauce in part, Sables de Fontainebleaux, Hempstead beds.)	Appearance of the genera *Rhinoceros* (?), *Tapir*, *Palæochœrus*, shrew, *Plesiosorex*, *Mysarachne*, mole, musk-rat, *Lutrictis*, *Palæonycteris*, *Tetracus*. Disappearance of *Palæotherium*, *Anoplotherium*. Reign of *Hyopotamus* and *Anthracotherium*.
Middle. (Calcaire de Brie, &c.)	Appearance of the genera *Cadurcotherium*, *Hyrachius*, *Entelodon*, *Anthracotherium*, *Dacrytherium*, *Chalicotherium*, *Tragulohyus*, *Lophiomeryx*, *Hyœmoschus* (?), *Gelocus*, *Dremotherium*, *Thereutherium*, dog (?), civet, martin, *Plesictis*, *Plesiogale*, *Ælurogale*, *Rhinolophus*, *Necrolemur*.
Lower. (Lacustrine gypsum of Paris, beds of Vaucluse, St. Hippolyte, Caton, Souvignargues, Bembridge beds.)	Appearance of the genera opossum, *Chœropotamus*, *Tapirulus*, *Anoplotherium*, *Eurytherium*, *Cainotherium*, *Anchilophus*, *Acotherulum*, *Cebochœrus*, *Xiphodon*, *Amphimeryx*, *Plesiarctomys*, dormouse (?), *Trechomys*, *Galethylax* (?), *Hyænodon*, *Adapis*. Reign of pachyderms. The carnivora have still partly marsupial characters.

§ 2. Local Development.

Britain.—Oligocene strata are but sparingly developed in this country. They occur in the Hampshire basin and Isle of Wight, resting conformably upon the top of the Eocene deposits, and consisting of sands, clays, marls, and limestones, in thin-bedded alternations. These strata were accumulated partly in the sea, partly in brackish, and partly in fresh water. They were hence named by Edward Forbes "the fluvio-marine series," and were subdivided by him as under, in descending order:[3]

Hempstead Beds.—Corbula beds (marine). Brown and greenish nodular clays and shelly beds (*Corbula vectensis*, *C. pisum*, *Cyrena semistriata*, *Cerithium plicatum*, Cyprids, &c.)	9ft. 6in.
Upper fresh-water and estuary marls.—(*Cerithium plicatum*, *Corbula vectensis*, *Cerithium elegans*, *Cyrena semistriata*, *Euchilus* (*Rissoa*) *Chastelli*, *Melania Nystii* (*inflata*), *Unio Austeni*, &c.)	40ft.
Middle fresh-water and estuary marls.—(*Cyrena semistriata*, *Paludina lenta*, *Cerithium Sedgwickii*, *Melania fasciata*, *Panopæa minor*, *P. Gibbsii*, &c.)	50ft.
Lower fresh-water and estuary marls.—(*Melania muricata*, *Melanopsis carinata*, *Euchilus* (*Rissoa*) *Chastelli*, *Paludina lenta*, with *Chara*, *Gyrogonites*, and other aquatic and terrestrial plants)	65ft.

[1] A. Milne Edwards, *Oiseaux Fossiles*. Boyd Dawkins, *Early Man in Britain*, p. 54.
[2] *Les Enchainements du Monde Animal*, 1878, p. 4.
[3] In the work already cited, p. 843. They were classed as Upper Eocene.

Bembridge Beds.—Bembridge marls (*Potamaclis* (*Melania*) *turritissima*, *Cerithium mutabile*, *Cyrena pulchra*, *Ostrea vectensis*) . . 62ft.
Limestone (*Limnæa longiscata*, *Hyalinia* (*Helix*) *d'Urbani*, *Helix occlusa*, *Planorbis obtusus*, *P. oligyratus*, *Cyclotus cinctus*, *Amphidromus* (*Bulimus*) *ellipticus*) . . . . 15 to 25ft.
Osborne or St. Helen's Beds.—Clays, marls, sands, and limestones (*Chara Lyelli*, *Cyrena obovata*, *Melanopsis carinata*, and numerous species of *Planorbis*, *Paludina*, &c.) . . . . 70 ft.
Headon Beds.—Upper, consisting of clays and thick beds of limestone, with abundance and variety of fossils (*Potamomya*, *Cyrena obovata*, *Nystia* (*Bulimus*) *polita*, *Melania muricata*, *Paludina lenta*, *Limnæa longiscata*). Middle, containing brackish-water and marine fossils (*Ostrea flabellula*, *O. callifera*, *Cytherea* (*Venus*) *incrassata*, *C. suborbicularis*, *Pleurotoma odontella*, *Murex sexdentatus*, *Voluta spinosa*, *Pisania labiata*, *Ancillaria buccinoides*, *Cancellaria muricata*, *Cerithium concavum*, &c. Lower, composed of fresh and brackish water beds with *Cyrena cycladiformis*, *Unio Solandri*, *Helix*, several species, &c. Among the more conspicuous fossils of the fresh-water part of the Headon beds are *Planorbis euomphalus*, *P. rotundatus*, *P. lens*, and other species, *Limnæa longiscata*, and other species, *Paludina lenta*; in the brackish-water beds *Potamomya plana*, and *Potamides cinctus*; and in the marine bands *Cytherea incrassata* . . . . 133 to 175 ft.

Considerable interest attaches to the marine band forming the middle division of the Headon beds, as it serves for a basis of correlation between the English strata and their equivalents on the Continent. The band is well seen in the Isle of Wight, and occurs also at Brockenhurst and other places in the New Forest. It has yielded up to the present time 235 species of fossils, almost all marine molluscs, but including also 14 species of corals. Of these organisms a considerable proportion is common to the Lower Oligocene of France, Belgium, and Germany, and 22 species are found in the Upper Bagshot beds.[1]

The Oligocene or fluvio-marine series of the Hampshire basin has yielded a few vertebrate remains. Among these are those of rays (*Myliobatis*), snakes (*Palæryx*), crocodiles, alligators, turtles (*Emys*, *Trionyx*, numerous species), and a cetacean (*Balænoptera*), while from the Bembridge beds have come the bones of a number of the characteristic mammals (*Anoplotherium*, two species, *Palæotherium*, six or more species, *Chæropotamus*, *Dichobune*, *Dichodon*, *Hyopotamus*, two species, *Lophiodon*, *Microchærus*, *Hyracotherium*). The top of the fluvio-marine series in the Isle of Wight has been removed in denudation, so that the records of the rest of the Oligocene period have there entirely disappeared.

It has been hitherto customary to consider as Miocene certain plant-bearing strata, of which a small detached basin occurs at Bovey Tracey, Devonshire, but which are mainly distributed in the great volcanic plateaux of Antrim and the west of Scotland. These strata have been regarded as equivalents of what are now termed Oligocene beds on the Continent. At the Bovey Tracey locality, which is not more than 80 miles from the Eocene leaf-beds of Bournemouth and the Isle of Wight, a small but interesting group of sand, clay, and lignite beds, from 200 to 300 feet thick, lies between the granite of Dartmoor and the Greensand hills, in what was evidently the hollow of a lake. From these beds Heer of Zurich, who has thrown so much light on the Tertiary floras of both

[1] A. von Koenen, *Q. J. Geol. Soc.* xx. (1864), 97. Duncan, *Op. cit.* xxvi. (1870), p. 66. J. W. Judd, *Op. cit.* xxxvi. (1880), p. 137. H. Keeping and E. B. Tawny, *Op. cit.* xxxvii. (1881), p. 85.

the Old World and the New, has described about 50 species of plants, which, he says, place this Devonshire group of strata on the same geological horizon with some part of the Molasse or Oligocene (lower Miocene) groups of Switzerland. Among the species are a number of ferns (*Lastræa stiriaca*, *Pecopteris* (*Osmunda*) *lignitum*, &c.); some conifers, particularly *Sequoia Couttsiæ*, the matted debris of which forms one of the lignite beds; cinnamon trees, evergreen oaks, custard-apples, eucalyptus, spindle-trees, a few grasses, water-lilies, and a palm (*Palmacites*). Leaves of oaks, figs, laurels, willows, and seeds of grapes have also been detected—the whole vegetation implying a subtropical climate.[1] More recently, however, Mr. Starkie Gardner has expressed the opinion that this flora is on the same horizon as that of Bournemouth, that is, in the middle Eocene group.[2] If this view be established the volcanic rocks of the north-west, with their leaf-beds, may be also relegated to the Eocene period. In the meantime, however, they are placed in the Oligocene series as probable equivalents of the brown-coal and molasse of the Continent. These leaf-beds occur in thin local patches intercalated among the great basalt-sheets already referred to (p. 258). The plateaux of Antrim, Mull, Skye, and adjacent islands are composed of successive outpourings of basalt, which are prolonged through the Faroe Islands into Iceland, and even far up into Arctic Greenland. In Ireland the basalts attain a maximum thickness of 900 feet; in Mull about 3000 feet. They are associated with tuffs, pitchstones, trachytes, and granitoid rocks, but more especially with a prodigious number of basalt dykes, which, as already stated (pp. 258, 555), probably occupy the fissures up which the basalt of the plateaux rose. It is evident that long-continued and vigorous volcanic action took place in these north-western regions.

Paris Basin.—In this area, where a perfect upward passage is traceable from the Eocene into the Oligocene beds, the latter are composed of the following subdivisions:[3]

Upper.		Meulières de Montmorency, very hard siliceous, cellular, fossiliferous, fresh-water limestones employed for millstones (*Limnæa*, *Bythinia*, *Planorbis*, *Valvata*, *Chara*). This deposit is replaced towards the south by the fresh-water Calcaire de Beauce. (80 feet.)
		Grès de Fontainebleau. Sands, and hard siliceous sandstones. At the top of this subdivision there occurs at Ormoy near Étampes and elsewhere a band of calcareous marl full of marine fossils (*Cardita Bazini*, *Cytherea incrassata*, *Lucina Héberti*).
Middle.	Sable d'Étampes.	Sables de Fontenay, Jeurre et Marigny, a thick accumulation of yellow ferruginous unfossiliferous sands, covering a large area around Paris, and serving as a foundation for most of the new military forts of that locality.
		Marls with oysters and marine molasse, containing at the base a bed of *Ostrea longirostris*, higher up a thick bed with *O. cyathula*, and at the top beds with *Corbula subpisum*.
		Calcaire de Brie.
		Green marls consisting of an upper mass of non-fossiliferous clay, and a lower group of fossiliferous laminated marls (*Cerithium plicatum*, *Psammobia plana*, *Cyrena convexa*).

[1] *Phil. Trans.* 1862.
[2] "British Eocene Flora," *Palæont. Soc.* 1879, p. 18.
[3] Dollfuss, *Bull. Soc. Géol. France*, 3e sér. vi. (1878), p. 293.

Lower.	Lacustrine Gypseous group.	White marls with *Limnæa strigosa*, *Planorbis planulatus*. Supra-gypseous blue marls, with very few fossils. Lacustrine gypsum (*Gyps lacustre*). The most important gypsum bed of the Paris basin, 26 feet thick, saccharoid in texture, containing skeletons and bones of mammals, fragments of terrestrial wood, and a few terrestrial shells (*Helix*, *Cyclostoma*, &c.). This deposit is continuous with the marine gypsum underneath it (p. 851).

Belgium.[1]—The succession of Oligocene beds in this country differs from that of France, and has received a different nomenclature, as follows:

Upper.			Wanting.
Middle.	Rupelian.	Marine.	White sands of Bolderberg (*Bolderian*). Clay of Boom and *Nucula* clay of Bergh, upwards of 40 species of fossils including *Nucula compta* (*Leda Lyelliana*), *Corbula subpisum* (="Septarienthon" of Northern Germany).
		Fluvio-marine.	*Cerithium* sands of Vieux Jonc (Klein Spauwen) and *Pectunculus* sands of Bergh. Henis clay. The fossils in this clay and the overlying sands are fluvio-marine (*Cyclostoma*, *Succinea*, *Pupa*; *Planorbis*, *Limnæa*, *Neritina*; *Cerithium*, *Melania*, *Bythinia*, *Cyrena*).
Lower.	Tongrian.	Marine.	Sands of Neerepen. Sands of Grimmertingen. The Tongrian deposits contain an abundant marine fauna = the Egeln beds of Germany.

Germany.[2]—In northern Germany, while true Eocene beds are wanting, the Oligocene groups are well developed both in their marine and fresh-water facies, and it was from their characters in that region that Beyrich proposed for them the term Oligocene. They occupy large more or less detached areas or basins, with local lithological and palæontological variations, but the following general subdivisions have been established:

Upper.	Brown-coal deposits of the Lower Rhine, &c., with a flora of less tropical, Indian, and Australian type, and more allied to that of sub-tropical North America (*Acer*, *Cinnamomum*, *Cupressinoxylon*, *Juglans*, *Nyssa*, *Pinites*, *Quercus*, &c.) Some marine beds in this division contain *Terebratula grandis*, *Pecten Janus*, *P. Münsteri*, &c.
Middle.	Stettin-sand and Septaria-clay (*Septarienthon*), with an abundant marine fauna (Foraminifera, *Pecten permistus*, *Leda deshayesiana*, *Axinus obtusus*, *Fusus Konincki*, *F. multisulcatus*, &c.). These beds are widely distributed in north Germany, and are usually the only representatives there of the Middle Oligocene deposits. In some places, however, a local brown-coal group occurs (*Alnus Kefersteini*, *Cinnamomum polymorphum*, *Populus Zaddachi*, *Taxodium dubium*).

[1] Mourlon, *Géol. Belg.*

[2] Beyrich, *Monatsbericht. Akad. Berlin*, 1854, p. 640, 1858, p. 51. A von Koenen, *Zeitsch. Deutsch. Geol. Ges.* xix. (1867), p. 23. Credner's *Geologie*.

Lower.

Egeln marine beds (*Ostrea ventilabrum, Arca appendiculata, Cardita Dunkeri, Cardium Hausmanni, Cytherea Solandri, Cerithium lævum, Pleurotoma Beyrichi, P. subconoidea, Voluta decora*, &c., and corals of the genera *Turbinolia, Balanophyllia, Caryophyllia, Cyathina*).

Amber beds of Königsberg—containing a bed (4 to 5 feet) of glauconitic sand, with abundant pieces of amber. The latter, derived from several species of conifers, have yielded a plentiful series of insects, arachnids, and myriapods, while the sands contain lower Oligocene marine mollusca.

Lower Brown-coal series—sands, sandstones, conglomerates, and clays with interstratified varieties of brown-coal (pitch-coal, earthy lignite, paper coal, wax-coal, &c.), a single mass of which sometimes attains a thickness of 100 feet or more. These strata may be traced intermittently over a large area of northern Germany. The flora of the brown-coal is largely composed of conifers (*Taxites, Taxoxylon, Cupressinoxylon, Sequoia*, &c.), but also with *Quercus, Laurus, Cinnamomum, Magnolia, Dryandroides, Ficus, Sassafras, Alnus, Acer, Juglans, Betula*, and palms (*Sabal, Flabellaria*). The general aspect of this flora most resembles that of the southern States of North America, but with relations to earlier tropical floras having Indian and Australian affinities.

Switzerland.[1]—Nowhere in Europe do Oligocene strata play so important a part in the scenery of the land, or present on the whole so interesting and full a picture of the state of Europe when they were deposited, as in Switzerland. Rising into massive mountains, as in the well-known Righi and Rossberg, they attain a thickness of more than 6000 feet. While they include proofs of the presence of the sea, they have preserved with marvellous perfection a large number of the plants which clothed the Alps, and of the insects which flitted through the woodlands. They form part of a great series of deposits which have been termed "Molasse" by the Swiss geologists. The Molasse was formerly considered to be entirely Miocene. The lower portions, however, are now placed on the same parellel with the Oligocene beds of the regions lying to the north, and consist of the following subdivisions:

Lower brown-coal or red Molasse (Aquitanian stage)—the most massive member of the Molasse, consisting of red sandstones, marls, and conglomerates (Nagelfluh), resting upon variegated red marls. It contains seams of lignite, and a vast abundance of terrestrial vegetation.

Lower marine Molasse (Tongrian stage)—sandstone containing marine and brackish-water shells, among which are *Ostrea cyathula, O. longirostris, Cyrena semistriata, Pectunculus obovatus, Cerithium plicatum*.

By far the larger portion of these strata is of lacustrine origin. They must have been formed in a large lake, the area of which probably underwent gradual subsidence during the period of deposition, until in Miocene times the sea once more overflowed the area. We may form some idea of the importance of the lake from the fact already stated, that the deposits formed in its waters are upwards of 6000 feet thick. Thanks to the untiring labours of Professor Heer, we know more of the vegetation of the mountains round that lake during Oligocene and Miocene time than we do of that of any other ancient geological period. The woods were marked by the predominance of an arborescent sub-tropical vegetation, among which evergreen forms were conspicuous, the whole having a decidedly American aspect. Among the plants were palms of American type, the Californian coniferous genus *Sequoia*, alders, birches, figs, laurels, cinnamon-trees, evergreen oaks, and other plants (see pp. 862, 867).

[1] Heer's *Urwelt der Schweiz.*

Central France.—Contemporaneously with the existence of the great Swiss Tertiary lake, one or more large sheets of fresh water lay in the heart of France. In these basins a series of marls and limestones (1500 feet thick in the Limagne d'Auvergne) accumulated, from which have been obtained the remains of nearly 100 species of mammals, including some palæotheres, like those of the Paris basin, a few genera found also in the Mayence basin, crocodiles, snakes, and numerous birds. This water basin appears to have been destroyed by volcanic explosions, which afterwards poured out the great sheets of lava, and formed the numerous cones and *puys* so conspicuous on the plateau of Auvergne.

Vienna Basin.[1]—This area contains a typical series of later Tertiary deposits, sometimes classed together as "Neogene." At the bottom lies a group of marls and sandstones known as the "Aquitanian stage," containing occasional seams of brown-coal and fresh-water beds, but with intercalations of marine strata. The marine layers contain *Cerithium plicatum*, *C. margaritaceum*, &c. The brackish and fresh water beds yield *Melania Escheri* and *Cyrena lignitaria*. Among the vertebrates are *Mastodon angustidens*, *M. tapiroides*, *Rhinoceros sansaniensis*, *Amphicyon intermedius*, *Anchitherium aurelianense*, and numerous turtles. These strata have suffered from the upheaval of the Alps, and may be seen sometimes standing on end. It is interesting also to observe that the subterranean movements east of the Alps culminated in the outpouring of enormous sheets of trachyte, andesite, propylite, and basalt in Hungary and along the flanks of the Carpathian chain into Transylvania. The volcanic action appears to have begun during the Aquitanian stage, but continued into later stages. Further curious changes in physical geography are revealed by the other "Neogene" deposits of south-eastern Europe. Thus in Croatia the Miocene marls, with their abundant land-plants, insects, &c., contain two beds of sulphur (the upper 4 to 16 inches thick, the under 10 to 15 inches), which have been worked at Radoboj. At Hrastreigg, Buchberg, and elsewhere, coal is worked in the Aquitanian stage in a bed sometimes 65 feet thick. In Transylvania, and along the base of the Carpathian Mountains, extensive masses of rock-salt and gypsum are interstratified in the "Neogene" formations.

Section III.—Miocene.

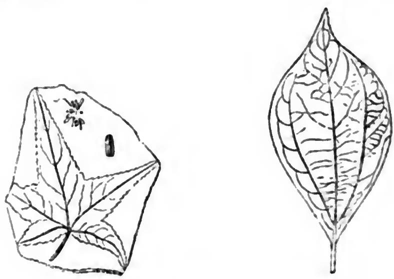
§ 1. General Characters.

The European Miocene deposits reveal great changes in the geography of the Continent as compared with its condition in earlier Tertiary time. So far as yet known, Britain was a land surface during the Miocene period; but a shallow sea extended towards the south-east and south, covering the lowlands of Belgium and the basin of the Loire and spreading over the south of France so as to connect the Atlantic Ocean north of Spain with the Mediterranean. It may have been an extension of the same sea that swept along the northern base of the now uplifted Alps, sending a long arm into the

[1] Suess, *Der Boden von Wien*, 1860. Th. Fuchs, *Erläuterungen zur Geol. Karte der Umgebungen Wiens*, 1873, and papers in *Zeitsch. Deutsch. Geol. Gesell.* 1877 (p. 653) *Jahrb. Geol. Reichsanst.* vols. xviii. *et seq.* Von Hauer's *Geologie*.

valley of the Rhine as far as the site of Mayence, which then probably stood at the upper end, the valley draining southward instead of northward. From the Miocene firth of the Rhine a sea-strait ran eastwards between the base of the Alps and the line of the Danube, filling up the wide basin of Vienna and spreading far and wide among the islands of south-eastern Europe.

Among the revolutions of the time not the least important in European geography was the continued uprise of the Alps by which the Eocene strata had been so convoluted and overthrown. These disturbances still went on in a diminished degree in Miocene time. One of their results was the restoration and extension of the wide lake or chain of lakes over the northern or molasse region of Switzerland in which the red molasse of Oligocene time had been deposited. The lacustrine deposits accumulated there have preserved with remarkable fulness a record of the terrestrial flora and fauna of the time.



a b

Fig. 411.—Miocene Plants.

a, Liquidambar Europæum (Braun.) ([illegible]); *b*, Cinnamomum Buchi (Heer) ([illegible]).

The flora indicates a decidedly tropical climate in the earlier part of the Miocene period in Europe, many of the plants having their nearest modern representatives in India and Australia. Among the more characteristic genera are *Sabal*, *Phœnicites*, *Libocedrus*, *Sequoia*, *Myrica*, *Quercus*, *Ficus*, *Laurus*, *Cinnamomum*, *Daphne*, *Persaonia*, *Banksia*, *Dryandra*, *Cissus*, *Magnolia*, *Acer*, *Ilex*, *Rhamnus*, *Juglans*, *Rhus*, *Myrtus*, *Mimosa*, and *Acacia*. In the later part of the period the climate, if we may judge from the character of the flora, had become more temperate; for among the more frequent plants are species of *Glyptostrobus*, *Betula*, *Populus*, *Carpinus*, *Ulmus*, *Laurus*, *Persea*, *Ilex*, *Podogonium*, and *Potamogeton*.

The fauna affords somewhat similar climatal indications. There occur such shells as *Ancillaria*, *Buccinum*, *Cancellaria*, *Cassis*, *Cypræa*, *Mitra*, *Murex*, *Pyrula*, *Strombus*, *Terebra*, *Arca*, *Cardita*, *Cardium*, *Cytherea*, *Mactra*, *Ostrea*, *Panopæa*, *Pecten*, *Pectunculus*, *Spondylus*,

Tapes, Tellina, &c. The mammalian forms present many points of contrast with those of older Tertiary time. Proboscideans now take a foremost place. Among the more important generic types of the

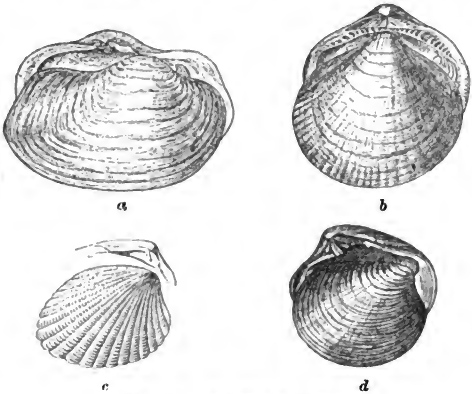


FIG. 412.—MIOCENE MOLLUSCS.

a, Panopæa Faujasii (P. Menardi) (Men. de la Groye) ([illegible]); *b*, Pectunculus glycimeris (P. pilosus) (Linn.) ([illegible]); *c*, Cardita affinis (Duj.); *d*, Tapes gregaria (Partsch.) ([illegible]).

time are the colossal *Mastodon* and *Deinotherium* (Fig. 415), the latter having tusks curving downwards from the lower jaw. With these are associated *Rhinoceros*, of which a hornless and a feebly horned species have been noted; *Anchitherium*, a small horse-like animal, about as

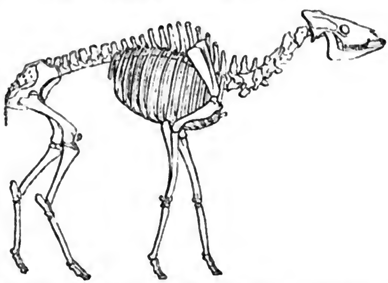


FIG. 413.—HELLADOTHERIUM DUVERNOYI (GAUDRY) ($\frac{1}{30}$).

big as a sheep, surviving from earlier Tertiary time; *Macrotherium*, a huge ant-eater; *Dricroceras*, a deer, allied to the living muntjak of eastern Asia, *Hyotherium*, an animal nearly related to the hog, and the tall giraffe-like *Helladotherium* (Fig. 413) described by M. Gaudry

from Attica. A number of living genera likewise made their entry upon the scene, such as the hog, otter, antelope, beaver, vole, and cat. Some of the most formidable animals were the sabre-toothed lions (*Machairodus*), and the earliest form of bear (*Hyænarctos*). The

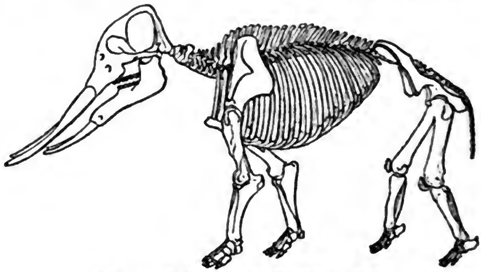


FIG. 414.—MASTODON ANGUSTIDENS (OWEN).
Reduced from restoration by M. Gaudry.

Miocene forests were also tenanted by apes, of which several genera have been detected. Of these, *Pliopithecus* was probably allied to the anthropoid apes; *Dryopithecus* (Fig. 415) may have been an anthropoid form, but is regarded by Owen as allied to the living

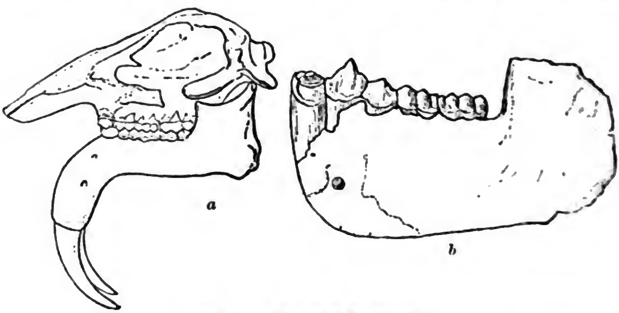


FIG. 415.—MIOCENE MAMMALS.
a, Deinotherium giganteum (Kaup.) reduced; *b*, Dryopithecus Fontani (Gaudry).

gibbons; *Oreopithecus* is supposed to have had affinities with the anthropoid apes, macaques, and baboons, and a species of *Colobus* is found in Wurtemberg.[1]

Considerable uncertainty must be admitted to rest upon the correlation of the later Tertiary deposits in different parts of Europe. In many cases their stratigraphical relations are too obscure to

[1] Gaudry, *Les Enchainements*, p. 306. Boyd Dawkins, *Early Man in Britain*, p. 57.

furnish any clue, and their identification has therefore to be made by means of fossil evidence. But this evidence is occasionally contradictory. For example, the remarkable mammalian fauna described by M. Gaudry from Pikermi in Attica has so many points of connection with the recognized Miocene fauna of other European localities that this observer classed it also as Miocene. He has pointed out, however, that in a shell-bearing bed underlying the ossiferous deposit of Pikermi some characteristic Pliocene species of marine mollusca occur. Hence, if we take marine mollusca as our guide, we must place the Pikermi beds in the Pliocene series.[1]

§ 2. Local Development.

France.—True Miocene deposits are not known to occur in Britain. In France, however, in the district known as Touraine, traversed by the rivers Loire, Indre, and Cher, there occurs a group of shelly sands and marls, which, as far back as 1833, was selected by Lyell as the type of his Miocene subdivision. These strata occur in widely extended but isolated patches, rarely more than fifty feet thick, and are known as "Faluns," having long been used as a fertilizing material for spreading over the soil. They present the characters of littoral and shallow-water marine deposits, consisting sometimes of a kind of coarse breccia of shells and shell-fragments, occasionally mixed with quartz-sand, and now and then passing into a more compact calcareous mass or even into limestone. Along a line that may have been near the coast-line of the period a few land and fresh-water shells, together with bones of terrestrial mammals, are found, but with these exceptions, the fauna is throughout marine. Among the fossils are numerous corals, and upwards of 300 species of molluscs, among which the following are characteristic: *Pholas Dujardini*, *Venus clathrata*, *Cardium turonicum*, *Cardita affinis*, *Trochus punctulatus*, *Cerithium Puymariæ*, *Buccinum blesense*, *B. spectabile*, with species of *Cypræa*, *Conus*, *Murex*, *Oliva*, *Ancillaria*, and *Fasciolaria*. This assemblage of shells indicates a warmer climate than that of southern Europe at the present time. The mammalian bones include the genera *Mastodon*, *Rhinoceros*, *Hippopotamus*, *Chæropotamus*, deer, &c., and extinct species of cetaceans, such as morse, sea-calf, dolphin, and lamantin.

In the region of Bordeaux and southward to the base of the Pyrenees, a large area is overspread with Oligocene deposits, equivalents of the younger Tertiary series of the Paris basin. Above these fresh-water and marine beds lie patches of faluns like those of Touraine. From the Miocene beds of other tracts of the south of France, remains of numerous interesting mammalia have been obtained. Among these are *Deinotherium giganteum*, *Mastodon angustidens*, *Rhinoceros Schleiermacheri*, *Machærodus cultridens*, *Helladotherium Duvernoyi*, and several apes and monkeys (*Pliopithecus*, *Dryopithecus*).

Belgium.—In this country the upper Oligocene strata of Germany are absent. In the neighbourhood of Antwerp certain black, grey, or greenish glauconitic sands ("Black Crag"), which in palæontological characters have both Miocene and Pliocene affinities, have been termed

[1] This point is further referred to at p. 878.

by some geologists Mio-pliocene. They are regarded as divisible, in ascending order, into, 1st, gravelly sands with cetacean bones (*Heterocetus*), fish-teeth, *Ostrea navicularis*, *Pecten Caillaudi*, &c. 2nd. Sands with *Pectunculus glycimeris* (*pilosus*). 3rd, Sands with *Panopæa Faujasii* (*Menardi*). The two lower subdivisions may be equivalents of part of the faluns of Bordeaux, &c.

Mayence Basin.—In this area an important series of marine, brackish, and fresh-water deposits occurs, which have been arranged by Fridolin Sandberger as follows:[1]

Pliocene—
- Uppermost brown-coal.
- Bone-sand of Eppelsheim.

Miocene—
- Clay, sand, &c., with leaves of *Quercus*, &c., Laubenheim.
- Limestone with *Litorinella acuta*.
- Corbicula beds with *Corbicula Faujasii*.
- Cerithium limestone and land-snail limestone.
- Sandstone with leaves.

Oligocene—
- Cyrena marl (*Cyrena semistriata*, *Cerithium plicatum*, *C. margaritaceum*).
- Septaria clay with *Leda deshayesiana*.
- Marine sand of Weinheim with *Ostrea callifera*, *Natica crassatina*.

The lower Miocene beds of this area present much local variation, some beds being full of terrestrial plants, some containing fresh-water, and others brackish-water and marine shells. Among the plants are species of *Quercus*, *Ulmus*, *Planera*, *Cinnamomum*, *Myrica*, *Sabal*, &c. The land-snail limestone contains numerous species of *Helix* and *Pupa*, with *Cyclostoma* and *Planorbis*. The *Cerithium* limestone contains marine shells, as *Perna*, *Mytilus*, *Cerithium* (*C. Rahtii*, *C. plicatum*), *Nerita*. Among the various strata bones of some of the terrestrial mammals of the time occur (*Microtherium*, *Palæomeryx*).

The Litorinella limestone, the most extensive bed in the series, is composed of limestone, marl, and shale, sometimes made up of *Litorinella acuta*, in other places of *Dreissena* (*Tichogonia*, *Congeria*) *Brardi*, or *Mytilus Faujasii*. Abundant land and fresh-water shells also occur. Of greater interest are the mammalian remains, which include those of *Deinotherium giganteum*, *Palæomeryx*, *Microtherium*, and *Hippotherium*. The flora of the higher parts of the Miocene series includes several species of oak and beech, also varieties of evergreen oak, magnolia, acacia, styrax, fig, vine, cypress, and palm.

Vienna Basin.—Overlying the Aquitanian stage (p. 861), where that is present, in other cases resting unconformably upon older Tertiary rocks, come the younger Tertiary or Neogene deposits of the Vienna basin—a large area comprising the vast depression between the foot of the eastern Alps near Vienna, the base of the plateau of Bohemia and Moravia, and the western slopes of the Carpathians. This tract communicated with the open Miocene sea by various openings in different directions. Its Miocene deposits are composed of two chief divisions or stages as follows, in descending order:[2]

[1] *Untersuchungen über das Mainzer Tertiärbecken*, 1853. *Die Conchylien des Mainzer Tertiärbeckens*, 1863.
[2] Von Hauer's *Geologie*, p. 617.

Sarmatian or Cerithium Stage.—Sandstones passing into sandy limestones and clays, or "Tegel" (the local name for a calcareous clay). According to Fuchs the following subdivisions occur around Vienna:

Upper Sarmatian Tegel, or Muscheltegel—distinguishable from the Hernals Tegel below by an abundance of shells (*Tapes gregaria*, *Ervilia*, *Cardium*, &c.), 295 feet.

Cerithium-sand—a yellow, abundantly shell-bearing, quartz-sand—the main source of water-supply at Vienna, where it is sometimes nearly 500 feet thick.

Hernals Tegel—sand and gravel, with *Cerithium*, *Rissoa*, *Paludina*, remains of turtles, fish, and land plants.

The Sarmatian stage is characterized by the prodigious number of individuals of a comparatively small number of species of shells, of which some of the most characteristic forms are *Tapes gregaria* (Fig. 412), *Mactra podolica*, *Ervilia podolica*, *Cerithium pictum*, *C. rubiginosum*, *Buccinum baccatum*, *Trochus podolicus*, *Murex sublævatus*. The general character of the fauna is that of a temperate climate, and is strongly contrasted with that of the Mediterranean stage in the absence of the affinities with tropical or sub-tropical forms, and even with those of the present Mediterranean, and on the other hand in some curious analogies with the living fauna of the Black Sea. Corals, echinoderms, bryozoa, foraminifera are absent or very rare, and the suggestion has been made that the change of the earlier Mediterranean fauna into that of the Sarmatian stage points to a gradual diminution of the salinity of the waters of the Vienna basin, as has happened with the existing Black Sea. The terrestrial flora is characterized by some plants that survived from the earlier or Mediterranean stage; but palms are entirely absent, and the American element in the flora is no longer surpassed by the preponderance of Asiatic types.

Mediterranean or Marine Stage.—A group of strata varying greatly from place to place in petrographical characters, with corresponding differences in fossil contents. Among the more important types of rock the following may be named.

Leithakalk, a limestone often entirely composed of organisms, and especially of reef-building corals, also bryozoa, foraminifera, echini (large clypeasters, &c.), large oysters (*Pecten latissimus* is specially characteristic), bones of mammals, and sharks' teeth. The Leithakalk passes frequently into sandy and marly beds, and into massive conglomeratic deposits (Leithakalk-schotter or conglomerate).

Tegel of Baden—fine blue clay, richly charged with shells, especially gasteropods (*Pleurotoma*, *Cancellaria*, *Fusus*, &c.) and foraminifera.

Marl of Gainfahren, Grinzing, Nussdorf, &c.—more calcareous than the Baden Tegel.

Sand of Pötzleinsdorf—a fine loose sand with *Tellina*, *Psammobia*, and many other lamellibranchs.

Sandstone of Sievering with many lamellibranchs, especially pectens and oysters.

These various strata are believed to represent different conditions of deposit in the area of the Vienna basin during the time of the Mediterranean stage. With them are grouped certain fresh-water beds (brown-coals, &c.), found along the margin of the basin, which are supposed to mark some of the terrestrial accumulations of the period.

The characteristically marine fauna of this stage is abundant and varied. It presents as a whole a more tropical character than that of the Sarmatian stage above. Some of its molluscan genera are now restricted to the warmer seas of the globe. The flora with its various kinds of palms had also a tropical aspect.

Switzerland.—Immediately succeeding the strata described on p. 860, as referable to the Oligocene series, come the following groups in descending order:

Upper fresh-water Molasse and brown-coal (Oeningen stage), consisting of sandstones, marls, and limestones, with a few lignite-seams and fresh-water

shells, and including the remarkable group of plant- and insect-bearing beds of Oeningen.

Upper marine Molasse (Helvetian stage)—sandstones and calcareous conglomerates, with 37 per cent. of living species of shells, which are to be found partly in the Mediterranean, and partly in tropical seas (*Pectunculus glycimeris* (*pilosus*), *Panopæa Faujasii* (*Menardi*), *Conus ventricosus*, &c.).

Lower fresh-water or Grey Molasse (Mayence stage)—sandstones with abundant remains of terrestrial vegetation, and containing also an intercalated marine band with *Cerithium lignitarum*, *Venus clathrata*, *Murex plicatus*, &c.

In the Oeningen beds, so gently have the leaves, flowers, and fruits fallen, and so well have they been preserved, that we may actually trace the alternation of the seasons by the succession of different conditions of the plants. Selecting 482 of those plants which admit of comparison, Heer remarks that 131 might be referred to a temperate, 266 to a subtropical, and 85 to a tropical zone. American types are most frequent among them; European types stand next in number, followed in order of abundance by Asiatic, African, and Australian. Great numbers of insects (between 800 and 900 species) have been obtained from Oeningen. Judging from the proportions of species found there, the total insect fauna may be presumed to have been then richer in some respects than it now is in any part of Europe. The wood-beetles were specially numerous and large. Nor did the large animals of the land escape preservation in the silt of the lake. We know, from bones found in the Molasse, that among the inhabitants of that land were species of tapir, mastodon, rhinoceros, and deer. The woods were haunted by musk-deer, apes, opossums, three-toed horses, and some of the strange, long-extinct Tertiary ruminants, akin to those of Eocene times. There were also frogs, toads, lizards, snakes, squirrels, hares, beavers, and a number of small carnivores. On the lake the huge *Deinotherium* floated, mooring himself perhaps to its banks by the two strong tusks in his under jaws. The waters were likewise tenanted by numerous fishes (of which 32 species have been described, all save one referable to existing genera), crocodiles, and chelonians.

Greenland.[1]—One of the most remarkable geological discoveries of recent times has been that of Tertiary plant beds in North Greenland. Heer has described a flora extending at least up to 70° N. lat., containing 137 species, of which 46 are found also in the central European Miocene basins. More than half of the plants are trees, including 30 species of conifers (*Sequoia*, *Thujopsis*, *Salisburia*, &c.), besides beeches, oaks, planes, poplars, maples, walnuts, limes, magnolias, and many more. These plants grew on the spot, for their fruits in various stages of growth have been obtained from the beds. From Spitzbergen (78° 56′ N. lat.) 136 species of fossil plants have been named by Heer. But the latest English Arctic expedition brought to light a bed of coal, black and lustrous like one of the Palæozoic fuels, from 81° 45′ lat. It is from 25 to 30 feet thick, and is covered by black shales and sandstones full of land-plants. Heer notices 26 species, 18 of which had already been found in the Arctic Miocene zone. As in Spitzbergen, the conifers are most numerous (pines, firs, spruces, and cypresses), but there occur also the arctic poplar, two species of birch, two of hazel, an elm, and a viburnum. In addition to

[1] Heer, "Flora Fossilis Arctica," *Q. J. Geol. Soc.* 1878, p. 66. Nordenskiöld, *Geol. Mag.* iii. (1876), p. 207. In this paper sections with lists of the plants found in Spitzbergen are given.

these terrestrial trees and shrubs the stagnant waters of the time bore water-lilies, while their banks were clothed with reeds and sedges. When we remember that this vegetation grew luxuriantly within 8° 15′ of the North Pole, in a region which is in darkness for half of the year, and is now almost continuously buried under snow and ice, we can realize the difficulty of the problem in the distribution of climate which these facts present to the geologist.

India.—The Oligocene and Miocene deposits of Europe have not been satisfactorily traced in Asia. As already stated, the upper part of the massive Nari group of Sind may represent some part of these strata. The Nari group is succeeded in the same region by the Gaj group 1000 to 1500 feet thick, chiefly composed of marine sands, shales, clays with gypsum, sandstones, and highly fossiliferous bands of limestone. The commonest fossils are *Ostrea multicostata*, and the urchin *Breynia carinata*. Some of the species are still living, and the whole aspect of the fauna shows it to be later than Eocene time. The uppermost beds are clays with gypsum, containing estuarine shells and forming a passage into the important Manchhar strata. The Manchhar group of Sind consists of clays, sandstones, and conglomerates, sometimes probably 10,000 feet thick, divisible into two sections, of which the lower may possibly be Miocene, while the upper may represent the Pliocene Siwalik beds (p. 879). As a whole this massive group of strata is singularly unfossiliferous, the only organisms of any importance yet found in it being mammalian bones, of which 22 or more species have been recognized. All of these occur in the lower section of the group. They include the carnivore *Amphicyon palæindicus*, three species of *Mastodon*, one of *Deinotherium*, two of *Rhinoceros*, also one of *Sus*, *Chalicotherium*, *Anthracotherium*, *Hyopotamus*, *Hyotherium*, *Dorcatherium* (two), *Manis*, a crocodile, a chelonian, and an ophidian.[1]

North America.—The Yorktown group succeeds the Alabama group (p. 853), and comprises strata of sand and clay, which extend over a large area in the seaward part of the eastern States. Their organic remains (comprising molluscs, with remains of sharks, seals, walruses, whales, &c.) show them to have been chiefly laid down in a shallow sea. Westward, in the Upper Missouri region, and across the Rocky Mountains into Utah and adjacent Territories, strata assigned to the same geological period have been termed the White River group. They were laid down in great lakes, and attain thicknesses of 1000 to 2000 feet. The organic remains of these ancient lakes, so well studied by Leidy, Marsh, and Cope, embrace examples of three-toed horses (*Anchitherium*, *Miohippus*, *Mesohippus*), tapir-like animals, differing from those of the older Tertiary strata (*Lophiodon*); hogs as large as rhinoceroses (*Elotherium*); true rhinoceroses (*Rhinoceros*, *Hyracodon*, *Diceratherium*), huge elephantoid creatures allied to the Deinoceras and tapir (*Brontotherium*, *Titanotherium*); also even-toed ruminant ungulates, some allied to the hog (*Oreodonts*), others like stags (*Leptomeryx*) and camels (*Poëbrotherium*, *Protomeryx*); carnivores (*Canis*, *Amphicyon*, *Machairodus*, *Hyænodon*), several of which are generically identical with European Tertiary wolves, lions, and bears. Among the smaller forms are the remains of the earliest known beavers (*Palæocastor*).

[1] Medlicott and Blanford's *Geology of India*, p. 472.

Section IV.—Pliocene.

§ 1. General Characters.

The tendency towards local and variable development which is increasingly observable as we ascend through the series of Tertiary deposits reaches its culmination in those to which the name of Pliocene has been given. The only European area in which Pliocene strata attain any considerable dimensions as rock-masses is in the basin of the Mediterranean, especially along both sides of the Apennine chain and in Sicily. In that region, reaching a thickness of several thousand feet, they were accumulated during a slow depression of the sea-bottom, and their growth was brought to an end by the subterranean movements which culminated in the outbreak of Etna, Vesuvius, and the other late Tertiary Italian volcanoes, and

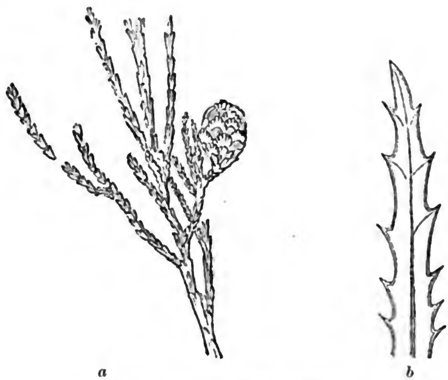


Fig. 416.—Pliocene Plants.
a, Glyptostrobus Europæus (Brongn.) (½); *b*, Hakea exalata (Heer).

in the uprise of the land between the base of the Apennines and the sea on either side of the peninsula. Elsewhere the marine Pliocene beds of Europe, local in extent and variable in character, reveal the beds of shallow seas, the elevation of which into land completed the outlines of the Continent at the close of Tertiary time. Here and there in south-eastern Europe evidence exists of the gradual isolation of portions of the sea into basins somewhat like those of the Aralo-Caspian depression, with a brackish or less purely marine fauna. In some portions of these basins, however, as in the Karabhogas Bay of the existing Caspian Sea, such concentration of the water took place as to give rise to extensive accumulations of salt and gypsum. In a few localities fluviatile and lacustrine deposits of the Pliocene period

have been preserved, from which numerous remains of terrestrial vegetation and mammals have been obtained.

The Pliocene **flora** is transitional between the luxuriant evergreen vegetation of the Miocene period and that of modern Europe. From the evidence of the beds in the upper part of the valley of the Arno above Florence it is known to have included species of pine, oak, evergreen oak, plum, plane, alder, elm, fig, laurel, maple, walnut, birch, buckthorn, hickory, sumach, sarsaparilla, sassafras, cinnamon, glyptostrobus, taxodium, sequoia, &c.[1] The researches of Count de Saporta have shown that the flora of Meximieux, near Lyons, comprised species of bamboo, liquidambar, rose-laurel, tulip-tree, maple, ilex, glyptostrobus, magnolia, poplar, willow, and other familiar trees.[2] The marked abundance of evergreen forms gave the flora a southern aspect, particularly in the older half of the Pliocene period. There is evidence, however, that a marked refrigeration of climate was in gradual progress, during which the plants specially characteristic of warmer latitudes one by one retreated from the European region.

FIG. 417.—ELEPHAS MERIDIONALIS (NESTI). Crown of molar.

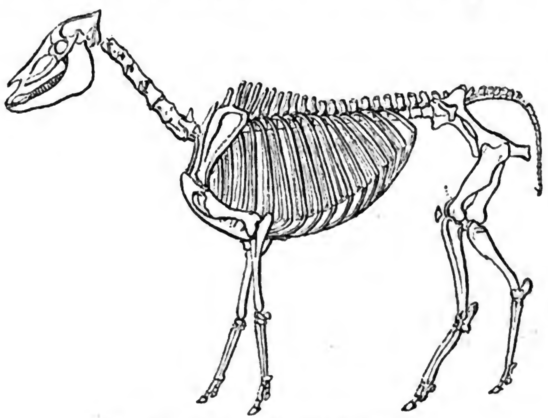


FIG. 418.—HIPPARION GRACILE (GAUDRY) ($\frac{1}{25}$).

The **fauna** of the Pliocene period still retained a number of the now extinct types of earlier time such as the *Deinotherium* and

[1] Gaudin, *Feuilles fossiles de la Toscane.* Gaudin et Strozzi, *Contributions à la flore fossile italienne.* Lyell, *Elements*, p. 190.

[2] "Recherches sur les Végétaux Fossiles de Meximieux," *Archiv. Mus. Lyon*, i. (1875-6).

Mastodon. It was characterized also by troops of rhinoceros, hippopotamus, and elephant; by large herds of herbivora, including numerous forms of gazelle, antelope, deer, and types intermediate between still living genera. Among these were some colossal ruminants, including a species of giraffe and the extinct genus *Helladotherium*, and other types met with among the Siwalik beds of India (*Sivatherium*, Fig. 424, *Bramatherium*). The Equidæ were represented by the existing *Equus*, and by extinct forms, one of the most abundant of which was *Hipparion* (Fig. 418), like a small ass or quagga, with three toes on each foot, only the central one actually reaching the ground. There were likewise species of ox, cat, bear, and hyæna, and numerous apes (*Mesopithecus*, Fig. 419), the remains of which have been met with 14° further north in Europe than their descendants now live.

The advent of a colder period is well shown in the younger

Fig. 419.—Mesopithecus Pentelici (Gaudry).

Pliocene beds of England, where a number of northern mollusca make their appearance. The proportion of northern species increases rapidly in the next succeeding or Pleistocene beds. The Pliocene period therefore embraces the long interval between the warm temperate climate of the later ages of Miocene and the cold of Pleistocene time. According to Professor Prestwich, the evidence of change of climate derivable from the English Pliocene mollusca may be grouped as follows:

	Species now restricted to	
	Northern Seas.	Southern Seas.
Norwich Crag	19	11
Red Crag	23	32
White Crag	14	65

The percentage of northern species in the White Crag is 5·0, in the Red Crag 10·7, in the Norwich Crag 14·6.[1]

[1] Prestwich, *Q. J. Geol. Soc.* xxvii. Lyell, *Antiquity of Man*, chap. xii. Searles Wood, "Crag Mollusca," *Palæont. Soc.*

§ 2. Local Development.

Britain.—In the Pliocene period, after a long period of exposure as a land surface during which a continuous and ultimately stupendous subaerial denudation was in progress, Britain underwent a gentle but local subsidence. We have no evidence of the extent of this depression. All that can be affirmed is that the south-eastern counties of England began to subside, and on their submerged surface some sandbanks and shelly deposits were laid down, very much as similar accumulations now take place on the bottom of the North Sea. These formations, termed "Crag," are subdivided, according to their proportion of living species of shells, into the following groups:

Forest Bed group		10 to 70 ft.
Chillesford beds	Chillesford Clay	1 „ 8 „
	Chillesford Sand with shells	5 „ 8 „
Norwich Crag		5 „ 10 „
Red Crag		25 „
White Crag		40 „ 60 „

The White Crag (Suffolk, Coralline, or Bryozoan Crag), consisting of shelly sands and marls, is exposed in many places in the county of Suffolk. It contains 316 species of shells, of which 84 per cent. are still living. Among its characteristic forms are *Terebratula grandis*, *Lingula Dumortieri*, *Pecten opercularis*, *Pholadomya histerna*, *Astarte Omalii* (Fig. 421), *Pyrula reticulata*, *Voluta Lamberti* (Fig. 422), *Fascicularia aurantium* (Fig. 420). The name "coralline" was given to the formation from the immense number of coral-like polyzoa which it contains, no fewer than 140 species having been described.

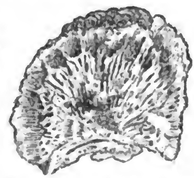


FIG. 420.—PLIOCENE POLYZOON.
Fascicularia aurantium (M. Edw.) (½).

The Red Crag is also a thin and local formation, consisting of a dark-red or brown ferruginous shelly sand. Of its molluscs, 92 per cent. are believed to be still living species, and, out of 25 species of corals, 14 are still natives of British seas. Some of the typical shells of this subdivision are *Trophon antiquum* (*Fusus contrarius*, Fig. 422), *Voluta Lamberti*, *Nassa reticosa*, *Purpura lapillus*, *P. tetragona*, *Pecten opercularis*, *Pectunculus glycimeris*, *Mactra arcuata*, *M. ovalis*, *Tellina obliqua*, *Cardium edule*, *Mytilus edulis*, and *Cyprina rustica*. Numerous mammalian remains have been obtained from these sands, including bones of *Mastodon arvernensis* and *M. tapiroides*, *Elephas meridionalis*, *Rhinoceros Schleiermacheri*, *Tapirus priscus*, *Sus antiquus*, *Equus plicidens*, *Hipparion*, *Hyæna antiqua*, *Felis pardoides*, *Cervus anoceros*, *Halitherium*, &c. There is reason to think that some of these remains may have been derived from the destruction of Miocene deposits.

The Norwich, Fluvio-marine, or Mammaliferous Crag consists of a few feet of shelly sand and gravel, containng, so far as known, 139 species of shells, of which 93 per cent. are still living. About 20 of the species are land or fresh-water shells. The name of mammaliferous was given from the large number of bones, chiefly of extinct species of elephant, recovered from this deposit. These fossils comprise *Mastodon arvernensis*, *Elephas meridionalis*, *E. antiquus*, *Hippopotamus major*, *Rhino-*

ceros leptorhinus, *Trogontherium Cuvieri*, a horse and deer, likewise the living species of otter and beaver. Among the mollusca the following are characteristic forms: *Paludina media*, *Hydrobia ventrosa*, *Turritella communis*, *Trophon scalariforme*, *Litorina litorea*, *Mytilus edulis*, *Nucula Cobboldiæ* (Fig. 421), *Cardium edule*. One interesting feature is the decided mixture of northern species of shells, such as *Rhynchonella psittacea*, *Scalaria grœnlandica* (Fig. 422), *Panopæa norvegica*, and *Astarte borealis* (Fig. 421). These may be regarded as the forerunners of the great invasion of Arctic plants and animals which, in the beginning of the

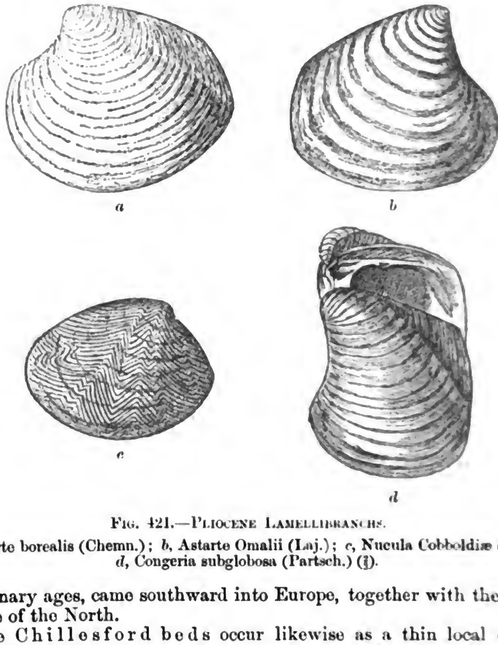


Fig. 421.—Pliocene Lamellibranchs.

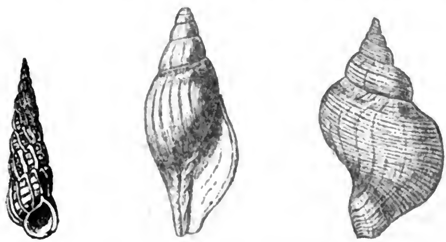
a, Astarte borealis (Chemn.); *b*, Astarte Omalii (Laj.); *c*, Nucula Cobboldiæ (Sow.); *d*, Congeria subglobosa (Partsch.) (⅓).

Quaternary ages, came southward into Europe, together with the severe climate of the North.

The Chillesford beds occur likewise as a thin local deposit chiefly in Suffolk. Among their organisms are *Mya truncata*, *Mactra ovalis*, *Nucula Cobboldiæ*, *Cyprina islandica*, *Astarte borealis*, *Tellina obliqua*. About two-thirds of the shells still live in Arctic waters. It is evident that, in these fragmentary accumulations of the Crag series, we have merely the remnants of some thin sheets of shelly sands and gravels laid down in the shallow waters of the North Sea, while that great lowering of the European climate was beginning which culminated in the succeeding or Glacial period.

The Forest-bed group comprises an interesting succession of beds, only a few feet in thickness, exposed for many miles at the base of the

great range of cliffs of glacial deposits on the north-east coast of Norfolk. These beds are of estuarine and marine origin, and include layers of peat and traces of a former land-surface which is marked by what has been termed the "rootlet bed." The designation "forest-bed," however, is unfortunately chosen, for the tree-stumps which suggested it appear to be in all cases drifted specimens. According to the recent researches of Mr. C. Reid of the Geological Survey, there is at the base a band of dark carbonaceous silt and peat with seeds, moss, &c. (lower fresh-water bed). This is surmounted by the "Forest bed" properly so called—a band of dark silt, clay, or loam, with numerous seeds, cones, stumps, and fragments of drift-wood, blocks of peat, bones of mammals, &c. Next comes another peaty layer (upper fresh-water bed), over which lie fine sands with clay and flint pebbles, containing *Leda myalis*, and other marine mollusca with united valves. Among the organic contents of the Forest-bed group are cones of Scotch fir and spruce, leaves of the white



a b c

FIG. 422.—PLIOCENE GASTEROPODS.

a, Scalaria grœnlandica (Chemn.); *b*, Voluta Lamberti (Sow.) (⅓); *c*, Trophon antiquum (Müll.) (½).

water-lily, yellow pond-lily, hornwort, blackthorn, bog-bean, oak, and hazel; species of marine, fresh-water, and land-shells (*Trophon antiquum, Nucula Cobboldiæ, Tellina, Pisidium amnicum, Unio pictorum, Paludina vivipara, Planorbis fontanus, Limnæa stagnalis, Succinea putris, Helix arbustorum*, &c.), of which *Corbicula fluminalis* and *Belgrandia marginata* no longer live in England, fifty species of mammals, two birds, two reptiles, four amphibians, and seventeen birds.[1]

[1] The mammals of the forest-beds afford an interesting glimpse of the fauna that preceded the advent of the Ice Age in central Europe and the adjoining seas. According to Mr. E. T. Newton's researches, the following is the list of recognized species: Carnivora—*Canis lupus? C. vulpes? Machairodus* sp., *Felidæ* (? genus), *Martes sylvatica, Gulo luscus, Ursus spelæus, U. ferox fossilis? Trichechus Huxleyi, Phoca* sp.; Ungulata—*Equus caballus fossilis, E. Stenonis, Rhinoceros etruscus, Rh. megarhinus? Hippopotamus major, Sus scrofa, Bos primigenius? Caprovis Savinii, Cervus bovides, C. capreolus, C. carnutorum? C. Dawkinsi, C. elaphus? C. etueriarum, C. Fitchii, C. Gunnii, C. latifrons, C. megaceros? C. polignacus, C. Sedgwickii, C. verticornis*; Rodentia—*Trogontherium Cuvieri, Castor Europæus, Arvicola amphibius, A. intermedius, A. arvalis, A. glareolus, Sciurus vulgaris? Mus sylvaticus*; Insectivora—*Talpa Europea, Sorex vulgaris, S. pygmæus, Myogale moschata*; Proboscidea—*Elephas antiquus, E. meridionalis, E. primigenius*; Cetacea—*Balænoptera? Monodon monoceros, Delphinus delphis, Delphinus*, sp. (*Geol. Mag.* 1880–82).

On the subject of the Forest-bed group see Lyell, *Phil. Mag.* 3rd ser. xvi. (1840),

France.—Pliocene deposits in various parts of France have yielded a considerable number of vertebrate remains. An older series, found in the south of the country at Montpellier, indicates by the association of its mammalian remains a warmer climate than that of the same region at the present day, for the list includes, besides species of *Hyæna*, *Felis*, *Machairodus*, *Lutra*, *Lagomys*, *Rhinoceros*, *Sus*, and *Cervus*, the extinct types of the Mastodon and *Hyænarctos*, as well as two species of ape. Later than these ossiferous strata are those of Perrier and other localities in Auvergne, where the apes are absent, the antelopes have dwindled in size and number, the deer have grown very abundant, true elephants for the first time appear, associated with a species of hippopotamus, nearly if not quite identical with the living African one; two kinds of hyæna, and the hipparion and machairodus that had survived from earlier times. This fauna indicates a decided change of climate to a more temperate character.[1]

Belgium.[2]—The neighbourhood of Antwerp has acquired celebrity for the remarkably fossiliferous character of certain sands which overlie the Black Crag described at p. 865. These strata, formerly classed as "Scaldisien" by Dumont, have recently been divided into a lower group, marked by the occurrence of *Isocardia cor*, and a higher containing *Trophon antiquum*. The lower sands, perhaps equivalents of the White Crag, have been named "Anversien" (Antwerpian) by Mourlon. They contain, among other shells, *Isocardia cor*, *Cyprina rustica*, *Cardita senilis*, *Lucina borealis*, *Astarte Omalii*, *Turritella incrassata*; also an abundant series of remarkable cetacean bones. The upper group ("Scaldisien" of Mourlon) may represent the Red Crag. It contains *Trophon antiquum*, *T. gracile*, *Voluta Lamberti*, *Purpura lapillus*, *P. tetragona*, *Nassa reticosa*, *Pecten maximus*, *P. Gerardi*, *Ostrea edulis*. Belgian Pliocene deposits, of which the precise horizons have not been determined, have yielded a large number of bones of marine mammalia, including seals, dolphins, and numerous cetaceans, as well as remains of fishes (*Carcharodon*, *Lamna*, *Oxyrhina*, &c.).

Mayence Basin.—Above the Miocene beds, described on p. 866, lies a group of sands and gravels with lignite (Knochen sand), from 20 to 30 feet thick, whence a considerable number of mammalian bones have been obtained at Eppelsheim, near Worms. Among these the *Deinotherium giganteum* occurs, showing the long survival of this animal in central Europe; also *Mastodon angustidens*, *Rhinoceros incisivus*, and other species, *Hippotherium gracile*, several species of *Sus*, five or more of *Cervus*, and some of *Felis*.

Vienna Basin.—In consecutive conformable order above the Miocene strata described on p. 866, come the highest Tertiary beds of this area, referred to the Pliocene period and known by the name of the "Congerian stage," from the abundance in them of the molluscan genus *Congeria* (Fig. 421). They are separable into two tolerably well defined zones, which in descending order are:

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p. 245, and his *Antiquity of Man*; Prestwich, *Q. J. Geol. Soc.* xxvii. pp. 325, 452; *Geologist*, 1861, p. 68; C. Reid, *Geol. Mag.* Dec. 2, iv. p. 300; vii. p. 55, 548, and his monograph on the Cromer district, which will shortly appear in the *Memoirs Geol. Surv.*

[1] Gaudry, *Matériaux pour l'Histoire des Temps Quaternaires*, 1876.

[2] Mourlon, *Géol. Belg.* Van Beneden, "Description des Ossements Fossiles des Environs d'Anvers," *Mus. Roy. Belgique*, vol. iv.

2. Belvedere-Schotter—a coarse conglomerate or gravel of quartz and other pebbles, occasionally yielding bones of large mammals; Belvedere-sand—a yellow micaceous sand, forming the lower member of the zone and containing in its more compact portions abundant terrestrial leaves. These strata resemble part of the alluvia of a large river. Their name is taken from the Belvedere in Vienna, where they are well developed.
1. Inzersdorf Tegel—a tolerably pure clay reaching a depth of often more than 300 feet. This deposit, the youngest Tertiary layer that is widely distributed over the Vienna basin, points to continued and general submergence. The facies of its fossils, however, shows that the water no longer communicated freely with the open sea, but seems rather to have partaken of a Caspian character. Among the conspicuous molluscs are *Congeria subglobosa, C. Partschi, C. triangularis, C. spathulata, C. Czjzeki, Cardium carnuntinum, C. apertum, C. conjungens, Unio atavus, U. moravicus, Melanopsis martiniana, M. impressa, M. vindobonensis, M. Bouéi.* The mammals include *Mastodon longirostris, M. angustidens, Deinotherium giganteum, Acerotherium incisivum, Hippotherium gracile,* antelope, pig, *Machairodus cultridens, Hyæna hipparionum.* The flora includes, among other plants, conifers of the genera *Glyptostrobus, Sequoia,* and *Pinus,* also species of birch, alder, oak, beech, chestnut, hornbeam, liquidambar, plane, willow, poplar, laurel, cinnamon, buckthorn, with the Asiatic genus *Parrotia,* the Australian proteaceous *Hakea* (Fig. 416), and the extinct tamarind-like *Podogonium.*

In other parts of the Austro-Hungarian empire interesting evidence exists of the gradual uprise of the sea-floor during later Tertiary time and the isolation of detached areas of sea, so that the south-east of Europe must then have presented some resemblance to the great Aralo-Caspian depression of the present time. The Congeria stage brings before us the picture of an isolated gulf gradually freshening, like the modern Caspian, by the inpouring of rivers; but on both sides of the Carpathian range there were bays nearly cut off from the main body of water, and exposed to so copious an evaporation without counterbalancing inflow that their salt was deposited over the bottom. Of the Transylvanian localities on the south side of the mountains the most remarkable is Parajd, where a mass of rock-salt has been accumulated having a maximum of 7550 feet in length, 5576 feet in breadth, and 590 feet in depth, and estimated to contain upwards of 10,595 millions of cubic feet. On the northern flank of the Carpathians near Cracow lie the famous and extensive salt-works of Wieliczka, with their massive beds of pure and impure rock-salt, gypsum, and anhydrite, some of the strata being full of fossils characteristic of the upper zones of the Vienna basin.

The south-east of Europe during later Tertiary time was the scene of abundant volcanic action, and the outpourings of trachyte, rhyolite, basalt, and tuff were specially abundant over the low districts to the south of the Carpathian chain.

Italy.—In this country Pliocene deposits are so extensively developed that they may be taken as a typical series for Europe. They form a range of low hills flanking both sides of the Apennine chain, and hence have been termed the "sub-Apennine series." They attain a thickness of upwards of 3000 feet, being most massive towards the south. They have been grouped into two divisions, the older consisting of blue marls and clays, sometimes calcareous, the upper of yellowish sands. In Sicily a threefold subdivision has been made out by Seguenza, who has traced the same arrangement throughout a large part of the mainland. The stages are in descending order:[1]

[1] *Bull. Soc. Géol. France,* 2e sér. xxv. 465.

3. Astian—yellow sands.
2. Plaisancian—blue clays or marls.
1. Zanclean—marly beds and light-coloured limestones.

Of these stages the first is characterized by a fauna of which nearly $\frac{9}{10}$ are peculiar species, and only 85 out of 504 species, or about 17 per cent., belong to living forms, which are nearly all found in the Mediterranean. Some of the common species of the deposit are *Janira flabelliformis, Terebratulina caput-serpentis, Rhynchonella bipartita, Dentalium triquetrum, Limopsis aurita, Leda dilatata, L. striata*, Phill. *Modiola phaseolina*. Tropical genera are well represented among the shells of the Italian Pliocene beds, while some of the still living Mediterranean genera occur there more abundantly, or in larger forms than on the present sea-bottom. The newer Pliocene beds attain in Sicily a thickness of 2000 feet or more, rising to a height of 3000 feet above the present sea-level, and covering nearly half of the island. One of their members is a yellowish limestone, sometimes remarkably massive and compact, and 700 or 800 feet thick, yet full of living species of Mediterranean shells, some of which even retain their colour and a part of their animal matter. It was during the accumulation of the Pliocene strata that the history of Etna began, the first stages being submarine eruptions, which were followed by the piling up of the present vast subaerial cone upon the upraised Pliocene sea-bottom.

The Italian Pliocene deposits, while chiefly of marine origin, contain also intercalations of lacustrine or fluviatile strata, in which remains of the terrestrial flora and fauna have been preserved. In the upper part of the valley of the Arno an accumulation of lacustrine beds attains a depth of 750 feet. The older portion consists of blue clays and lignites, with the abundant vegetation above referred to (p. 871). The upper 200 feet consists of sands and a conglomerate ("sansino"), and have yielded remains of *Mastodon Arvernensis, Elephas meridionalis, Rhinoceros etruscus, Hippopotamus major, Ursus, Hyæna, Felis*, &c.

Greece.—A remarkable series of mammalian remains brought to light from certain hard red clays alternating with gravels at Pikermi, in Attica, has been carefully worked out by M. Gaudry.[1] The list includes a monkey (*Mesopithecus*) intermediate between the living *Semnopithecus* of Asia and the Macaques. The carnivores are represented by *Simocyon, Mustela. Promephitis, Ictitherium*,—a genus allied to the modern civet—*Hyænictis, Hyæna, Machairodus*, and several species of *Felis*; the rodents by *Hystrix*, allied to the common porcupine; the edentates by the gigantic *Ancylotherium*; the proboscideans by *Mastodon* and *Deinotherium*; the pachyderms by Rhinoceros (several species), *Acerotherium, Leptodon, Hipparion*, and a gigantic wild boar (*Sus erymanthius*); the ruminants by *Camelopardalis*, of the same size as the living giraffe, *Helladotherium*—a form between the giraffe and the antelopes—three

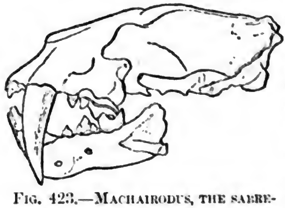


FIG. 423.—MACHAIRODUS, THE SABRE-TOOTHED LION.

[1] *Animaux fossiles et Géologie de l'Attique*, 4to, 1862, with volume of plates. See also Roth and Wagner, *Abhandl. Bayer. Akad.* vii. (1854).

species of true antelope—*Palæotragus*, an antelope-like animal, *Palæoryx*, somewhat like the living African gemsbok, and *Palæoreas*, allied to the African eland and the gazelles—*Gazella*, a true gazelle, *Dremotherium*, probably a hornless ruminant like the living chevrotains. A few remains of birds have also been met with, including a *Phasianus*, related to our pheasant, a *Gallus*, smaller than our common domestic fowl, a *Grus*, closely related to the living crane; also bones of a turtle and a saurian (*Varanus*). This fauna is remarkable for the extraordinary abundance of its ruminants, the colossal size of many of the forms, such as the giraffe and *Helladotherium*, the singular rarity of the smaller mammals, the marked African facies which runs through the whole series, and the number of transitional types which it contains. The Pikermi beds have been classed as upper Miocene, but the occurrence of some true Pliocene species of shells below them, and the marked preponderance of living types, justify their being placed in a later stage of the Tertiary series.

India.—Not less important than the massive Pliocene accumulations of the Mediterranean basin are those which have been formed in Sind, the Punjab, and other north-western tracts of India. In Sind the noteworthy fact has been made out by the Indian Geological Survey that from the upper Cretaceous to the Pliocene beds the whole succession of strata, with some trifling local exceptions, is conformable and continuous; yet contains evidence of alternations of marine and terrestrial conditions, the latest marine intercalations being of Miocene date. The upper division of the Manchhar group (p. 869) is not improbably referable to the Pliocene period. It consists of clays, sandstones, and conglomerate, 5000 feet thick, which have yielded some indeterminable fragmentary bones. Similar strata cover a vast area in the Punjab. They are admirably exposed in the long range of hills termed the Sub-Himalayas, which from the Brahmaputra to the Jhelum, a distance of 1500 miles, flank the main chain, and consist chiefly of soft massive sandstone disposed in two parallel lines of ridge having a steep southerly face and a more gentle northerly slope, and separated by a broad flat valley. These strata, having an aggregate thickness of between 12,000 and 15,000 feet, contain representatives of the older Tertiary or Nummulitic series, followed by younger Tertiary deposits which are classed together in what has been termed the Siwalik group. This group is of fresh-water origin, for its included organisms are entirely land or fresh-water forms. Its component clays, sandstones, and conglomerates have been deposited by great rivers, which appear to have flowed from the Himalayan chain by the same outlets as their modern representatives. These deposits vary according to their position relatively to the great rivers. They have been involved in the last colossal movements whereby the Himalayas have been upheaved, yet their structure shows that the same distribution of the watercourses has been maintained as existed before the disturbance. In this instance, as in that of the Green River through the Uinta range in western America, the inference seems to be legitimate that the elevation of the mountains must have proceeded so slowly that the erosion of the river kept pace with it, and the positions of the valleys were therefore not sensibly changed. (See p. 920.)

The Siwalik fauna consists partly of a few land or fresh-water molluscs, some, if not all, of which are identical with living species; but

chiefly of mammalia, of which no fewer than about 93 species have been determined belonging to 48 genera, of which those that are now extinct are marked in the subjoined list with an asterisk:[1]

Primates—*Macacus*, 2 sp.; *Semnopithecus*, 2.
Carnivora—*Felis*, 2; *Machairodus* * (*Drepanodon*), 1; *Pseudælurus*,* 1; *Ictitherium*,* 1; *Hyæna*, 1; *Canis* (*Vulpes*), 1; *Amphicyon*,* 1; *Ursus*, 1; *Hyænarctos*,* 2; *Mellivora*, 1; *Meles*, 1; *Lutra*, 1; *Enhydriodon*,* 1.
Proboscidea—*Elephas*, 7 (*Euelephas*, 1; *Loxodon*, 1; *Stegodon*,* 5); *Mastodon*,* 4 (*Pentalophodon*,* 1; *Tetralophodon*,* 2; *Trilophodon*,* 1).
Ungulata Perissodactyla—*Rhinoceros*, 6; *Acerotherium*,* 1; *Listriodon*,* 1; *Equus*, 2; *Hipparion*,* 2.
Ungulata Artiodactyla — *Hippopotamus* (*Hexaprotodon* *), 1; *Hippopotamodon*,* 1; *Tetraconodon*,* 1; *Sus*, 3; *Hippohyus*,* 2; *Chalicotherium*,* 1; *Merycopotamus*,* 1; *Cervus*, 3; *Dorcatherium*,* 2; *Camelopardalis*, 2; *Sivatherium*,* 1; *Hydaspitherium*,* 3; *Bos*, 3; *Bison*, 1; *Bubalus*, 2; *Peribos*,* 1; *Amphibos*,* 1; *Hemibos*,* 1; *Antilope*, 4; *Capra*, 2; *Ovis*, 1; *Camelus*, 1.
Rodentia—*Mus*, 1; *Rhizomys*, 1; *Hystrix*, 1.

In this list there is considerable resemblance to the grouping of mammalia in the Pikermi deposits just referred to, particularly in the preponderance of large animals, the absence or rarity of the smaller forms (rodents, bats, insectivores), and the marked Miocene aspect of certain parts of the fauna. Mr. Blanford, however, has recently shown that though usually classed as Miocene the Siwalik fauna has such relations to Pliocene and recent forms as are found in no true Miocene fauna. Among the genera 12 are unknown elsewhere, 7 are Miocene and Pliocene; of the still living genera 9 range back in Europe to upper Miocene time, 10 only to Pliocene, while 6 are only known elsewhere as living forms or as occurring in post-Pliocene beds. The large preponderance of species belonging to such familiar genera as *Felis*, *Canis*, *Ursus*, *Elephas*, *Equus*, *Cervus*, *Bos*, *Antilope*, and *Capra*, gave the whole assemblage a singularly modern aspect. It should be added that associated with the mammals are six determinable reptiles, of which three are recent; four or five kinds of birds, of which one is probably identical with the living ostrich, and a number of land and fresh-water shells of existing species.[2]

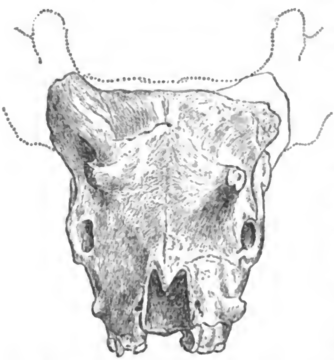


Fig. 424.—Sivatherium giganteum (Falc.). A gigantic two-horned form of antelope found in the Siwalik beds of India.

North America.—The uppermost division of the Tertiary series of the eastern United States has received the name of the Sumter group,

[1] Medlicott & Blanford, *Geology of India*, p. 577. Blanford, *Brit. Assoc.* 1880, p. 577.
[2] Blanford, *Brit. Assoc.* 1880, p. 578.

and is believed to be the equivalent, more or less fully, of the European Pliocene deposits. In the Carolina States beds of loam, clay, or sand, lying in hollows of the older Tertiary deposits, and containing from 40 to 60 per cent. of living marine shells, are referred to this group. In the Upper Missouri region, the White River group is overlaid by other fresh-water beds, 300 to 400 feet thick (Loup River group of Meek and Hayden, or Niobrara group of Marsh), from which an interesting series of vertebrate remains has been obtained. Among these are those of an eagle, a crane, and a cormorant; a tiger, larger than that of India, an elephant, a mastodon, several rhinoceroses, the oldest known camels (*Procamelus*, *Homocamelus*), equine animals of the genera *Protohippus*, *Pliohippus*, *Merychippus*, and *Equus*, of which the last was as large as the living horse. The remarkably oriental character of this fauna is worthy of special notice.

Australasia.—Though vast areas in this region are covered with strata which sometimes attain a depth of several hundred feet, containing both terrestrial and marine deposits, and which are referable to various parts of Cainozoic time, no satisfactory correlation of the beds with European equivalents has yet been made, if, indeed, such a correlation is at all probable or possible. All that can at present be affirmed is that a succession among these beds can be traced with an increasing proportion of recent species in the younger parts of the series. Throughout the whole of eastern Australia, including New South Wales and Queensland, no marine Tertiary fossils have been discovered. In the first-named colony, as well as in Victoria, beds occur containing terrestrial vegetation which has been referred to a late Tertiary age, as it consists of plants allied to those of the present forest-belt of Eastern Australia. The plant beds are often associated with auriferous gravels, and in some places have been buried under thick sheets of basalt. In South Australia and Victoria extensive marine accumulations occur referable to parts of the Tertiary periods. These consist of clays, sands, and limestones, often underlying wide-spread basalt-plateaux. They have yielded numerous foraminifera, especially at Mount Gambier and Murray Flats in South Australia: 40 species of corals, which are only slightly related to the living species of the surrounding seas, but include three European Tertiary species;[1] numerous echinoderms and polyzoa, and a large molluscan fauna, in which the genera *Waldheimia*, *Cucullæa*, *Pectunculus*, *Trigonia*, *Cypræa*, *Fusus*, *Haliotis*, *Murex*, *Mitra*, *Trivia*, *Turritella*, *Voluta*, &c., occur. The vertebrate organisms consist of fishes (of the world-wide genera *Carcharodon*, *Lamna*, *Otodus*, *Oxyrhina*), a few marsupials (*Bettongia*, *Nototherium*, *Phascolomys*, *Sarcophilus*), with some marine mammalia (*Squalodon*, *Arctocephalus*).

In the South Island of New Zealand a mass of sandy and calcareous strata, termed the "Oamaru formation," reaches an average thickness of from 1500 to 2000 feet, traceable to a height of 5000 feet in the Southern Alps. Out of 88 species of mollusca Captain Hutton accounts 12 (or 13½ per cent.) to be still living. These strata are supposed by some to be on the same general parallel as the Eocene, by others on that of the Oligocene or Miocene series of Europe. There is evidence that volcanic action was going on contemporaneously with their deposi-

[1] Duncan, *Q. J. Geol. Soc.* 1870, p. 3[illegible]

tion, for beds of palagonite-tuff, and other volcanic products are interstratified with them in some localities. Later in date is the "Pareora formation"—a succession of bluish or greenish sandy clay, with calcareous bands and concretions. Out of 154 marine mollusca Captain Hutton identifies 58 (or 37½ per cent.) with still living forms, and is therefore disposed to consider the group as Miocene.[1]

[1] Haast, *Geology of Canterbury*. Hutton's *Geology of Otago*.

PART V.—POST-TERTIARY OR QUATERNARY.

Under this division are included the various superficial deposits in which all the mollusca are of still living species. It is usually subdivided into two series—(1) an older group of deposits in which many of the mammals are of extinct species,—to this group the names Pleistocene, Post-Pliocene, and Diluvial have been given; and (2) a later series, wherein the mammals are all or nearly all of still living species, to which the names Recent, Alluvial, and Human have been assigned. These subdivisions, however, are confessedly very artificial, and it is often exceedingly difficult to draw any line between them.

In Europe and North America a tolerably sharp demarcation can usually be made between the Pliocene formations and those now to be described. The Crag deposits of the south-east of England show traces of a gradual lowering of the temperature during later Pliocene times. This change of climate continued to augment until at last thoroughly arctic conditions prevailed, under which the oldest of the Post-Tertiary or Pleistocene deposits were accumulated.

It is hardly possible to arrange the Post-Tertiary deposits in a strict chronological order, because we have no means of deciding, in many cases, their relative antiquity. In the glaciated regions of the northern hemisphere the various glacial deposits are grouped as the older division of the series under the name of Pleistocene. Above them lie younger accumulations such as river-alluvia, peat-mosses, lake-bottoms, cave-deposits, blown-sand, raised lacustrine and marine terraces, which, merging insensibly into those of the present day, are termed Recent or Prehistoric.

Section I.—Pleistocene or Glacial.

§ 1. General Characters.

Under the name of the Glacial Period or Ice Age, a remarkable geological episode in the history of the northern hemisphere is denoted.[1] The Crag deposits (p. 873) afford evidence of a gradual refrigeration of climate at the close of the Tertiary ages. This change of temperature affected the higher latitudes alike of the Old and the New World. It reached such a height that the whole of the north of Europe was buried under snow and ice, extending southwards even as far as Saxony. The Alps and Pyrenees were loaded with

[1] No section of geological history now possesses a more voluminous literature than the Glacial Period, especially in Britain and North America. For general information the student may refer to Lyell's *Antiquity of Man*, J. Geikie's *Great Ice Age*, J. Croll's *Climate and Time*, and for detailed descriptions, to the *Quart. Journ. Geol. Soc.*, *Geol. Mag.*, and *Amer. Journ. Science*, for the last fifteen or twenty years.

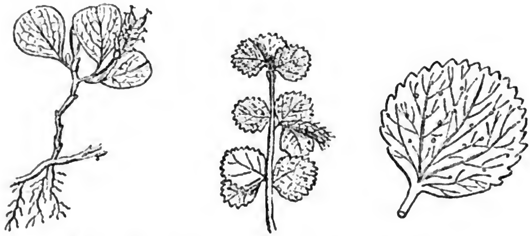
vast snow-fields, from which enormous glaciers descended into the plains, overriding ranges of minor hills on their way. The greater portion of Britain was similarly ice-covered. In North America also, Canada and the eastern States of the American Union down to about the 39th parallel of north latitude, lay under the northern ice-sheet. The effect of the movement of the ice was necessarily to remove the soils and superficial deposits of the land surface. Hence in the areas of country so affected, the ground having been scraped and smoothed, the glacial accumulations laid down upon it usually rest abruptly, and without any connection, on older rocks. Considerable local differences may be observed in the nature and succession of the different deposits of the glacial period, as they are traced from district to district. It is hardly possible to determine, in some cases, whether certain portions of the series are coeval or belong to different epochs. But the following leading facts have been established. First, there was a gradual increase of the cold, though with warm intervals, until the conditions of modern North Greenland extended as far south as Middlesex, Wales, the south-west of Ireland, and 50° N. lat. in central Europe, and about 39° N. lat. in Eastern America. This was the culmination of the Ice Age,—the first or chief period of glaciation. Then followed a long interval marked probably by a succession of warmer interglacial periods, and during some part of its continuance by a partial depression of the land and the spread of cold Arctic water over the submerged tracts, with abundant floating ice. The subsidence was succeeded by a re-elevation, with renewed augmentation of the snow-fields and glaciers,—a second period of glaciation. Very gradually, and after intervals of increase and diminution, the ice retired towards the north, and with it the Arctic flora and fauna that had peopled the plains of Europe, Canada, and New England. The existing snow-fields and glaciers of the Pyrenees, Switzerland, and Norway are remnants of the great ice-sheets of the glacial period, while the Arctic plants of the mountains are relics of the northern vegetation that covered the lowlands of Europe from Norway to Spain.

The general succession of events has been the same throughout all the European region north of the Alps, and in Canada, Labrador, and the north-eastern States, though of course with local modifications. The following summary embodies the main facts in the history of the Ice Age. Some local details are given in subsequent pages.

Pre-glacial Land-surfaces.—Here and there fragments of the land over which the ice-sheets of the glacial period settled have escaped the general extensive ice-abrasion of that ancient terrestrial surface, and have even retained portions of the forest growth that covered them. One of the best known of these fragments is the "Forest bed," already referred to (p. 874). Above that deposit there is seen here and there on the Norfolk coast a local or intermittent bed of clay containing remains of Arctic plants (*Salix polaris, Betula*

nana, &c. (Fig. 425). These relics of a terrestrial vegetation are drifted specimens, but they cannot have travelled far, and they probably represent a portion of the Arctic flora which had already found its way into the middle of England before the advent of the ice-sheet. Judging from the present distribution of the same plants, we may infer that the climate had become about 20° colder than it was during the time represented by the Forest-bed—a difference as great as that between Norfolk and the North Cape at the present day.[1]

Ice-worn Rocks.—At the base of the glacial deposits the solid rocks over the whole of northern Europe present the characteristic smoothed flowing outlines produced by the grinding action



a *b* *c*

Fig. 425.—ARCTIC PLANTS FROM GLACIAL BEDS.
a, Salix polaris (Wahlenb.) ($\frac{2}{3}$); *b*, Betula nana (Linn.); *c*, Leaf of same, showing the size to which it grows in more southern countries.

of land-ice (p. 413). Long exposed, this peculiar surface is apt to be effaced by the disintegrating action of the weather, though it retains its hold with extraordinary pertinacity. Along the fjords of Norway and the sea-lochs of the west of Scotland, it may be seen slipping into the water, smooth, bare, polished, and grooved as if the ice had only recently retreated. Inland, where a protecting cover of clay or other superficial deposits has been newly removed, the peculiar ice-worn surface is as fresh as that by the side of a modern glacier. Observations of the directions of the striæ have shown that on the whole these markings diverge from the main masses of high ground. This radiation is admirably seen in the British Islands, where each block of elevated land, such as the Grampians, the southern uplands of Scotland, and the hills of the Lake district, served as centres whence the ice flowed downwards and outwards in all directions into the plains or into the sea. In Scandinavia the ice-striæ run westwards and south-westwards on the Norwegian coasts, and eastwards or south-eastwards across the lower grounds of

[1] C. Reid, *Horizontal Section, No.* 127 *of Geol. Survey*, and Memoir on Cromer district in *Memoirs of Geol. Survey*.

Sweden. When the ice descended into the basin of the Baltic and the plains of northern Germany, it moved southwards and south-westwards, but seems to have slightly changed its direction in different areas and at different times. Its movements can be made out partly from the striæ on the solid rock, but more generally from the glacial drift which it has left behind. Thus it can be shown to have moved down the Baltic into the North Sea. At Berlin its movement must have been from east to west. But at Leipsic, as recently ascertained by Credner, it came from N.N.W. to S.S.E., being doubtless shed off in that direction by the high grounds of the Harz Mountains. Its southern limit can be traced with tolerable clearness from Jevennaar in Holland eastwards across the Rhine valley, along the base of the Westphalian hills, round the projecting promontory of the Harz, and then southwards through Saxony to the roots of the Erzgebirge. Passing next south-eastwards along the flanks of the Riesen and Sudeten chain, it sweeps across Poland into Russia, circling round by Kieff, and northwards by Nijni Novgorod towards the Urals. It has been estimated that, excluding Finland, Scandinavia, and the British Isles, the ice must have covered no less than 1,700,000 square kilometres of the present lowlands of Europe.

Some idea of the massiveness of the ice-sheet is obtainable from a consideration of the way in which the striæ run across important hill ranges, and athwart what might seem to be their natural direction. Whilst there was a general southward movement from the great snow-fields of Scandinavia, the high grounds of Britain were important enough to have their own independent ice, which, as the striæ show, radiated outward, some of it passing westwards into the Atlantic, and some of it eastward into the North Sea. So thick must it have been as it moved off the Scottish Highlands that it went across the broad plains of Perthshire, filling them up to a depth of at least 2000 feet, and passing across the range of the Ochil Hills, which at a distance of twelve miles runs parallel with the Highlands, and reaches a height of 2352 feet. Many mountains in the Highlands are glaciated up to heights of 3000 feet and more, while lakes at their feet 600 feet deep have been well ice-worn. It has been observed that the striæ along the lower slopes of a hill barrier run either parallel with the trend of the ground or slant up obliquely, while those on the summits may cross the ridge at right angles to its course, showing a differential movement in the great ice-sheet, the lower parts, as in a river, becoming embayed, and being forced to move in a direction sometimes even at a right angle to that of the general advance. On the lower grounds, also, the striæ, converging from different sides, unite at last in one general trend as the various ice-sheets must have done when they descended from the high grounds on either side and coalesced into one common mass. This is well seen in the great central valley of Scotland. Still more marked is the deflection of the striæ in Caithness and the Orkney and Shetland Islands. In these districts the general direc-

tion of the striation is from S.S.E., which, in Caithness, is nearly at right angles to what might have been anticipated. This deflection has been attributed to the coalescence of the ice from Norway and from the northern Highlands in the basin of the North Sea, and its subsequent progress along the resultant north-westerly line into the Atlantic. But it may have been due to the fan-shaped spreading out of the vast mass of ice descending into the Moray Firth; for the striæ on the south side of that inlet run E. by S., and at last S.E., on the north-east of Aberdeenshire, showing that the ice on the one hand turned southwards into the North Sea, until it met the N.E. stream from Kincardineshire and the valleys of the Dee and Don, while on the other it moved northward so as no doubt to join the Scandinavian sheet, and march with it into the Atlantic. The basin of the North Sea must have been choked up with ice in its northern parts, if not entirely. At that time England and the north-west of France were probably united, so that any portion of the North Sea basin not invaded by land-ice must have formed a lake, with its outlet by the hollow through which the Strait of Dover has since been opened. It has been suggested that during such a condition of things the widespread deposit termed Loess was formed, which covers so large a space in the lower plains of the Rhine and the north of Belgium (Hesbayan mud), and appears in the valleys of the south-east of England.

The ice is computed to have been at least between 6000 and 7000 feet thick in Norway, measured from the present sea-level. From the height at which its transported debris has been observed on the Harz, it is believed to have been at least 1470 feet thick there, and to have gradually risen in elevation as one vast plateau, like that which at the present time covers the interior of Greenland. Among the Alps it attained almost incredible dimensions. The present snowfields and glaciers of these mountains, large though they are, form no more than the mere shrunken remnants of the great mantle of snow and ice which then overspread Switzerland. In the Bernese Oberland, for example, the valleys were filled to the brim with ice, which, moving northwards, crossed the great plain, and actually overrode a part of the Jura Mountains; for huge fragments of granite and other rocks from the central chain of the Alps are found high on the slopes of that range of heights.

That the ice in its march across the land striated even the hardest rocks by means of the sand and stones which it pressed against them, is a proof that, to some extent at least, the terrestrial surface must have been at this time abraded and lowered in level. How far this erosion proceeded, or in other words, how much of the undoubtedly enormous denudation everywhere visible over the glaciated parts of Europe, is attributable to the actual work of land-ice, is a problem which may never be even approximately solved (see p. 338). The land had the same general features of mountain, valley, and plain as it has now, even before the ice settled down upon it. But

the prominences reached by the ice were rounded off and smoothed over, the pre-glacial soils and covering of weathered rock were ground up and pushed away, the valleys were deepened and widened, and the plains were strewn with ice-borne debris. It is obvious that the influence of the moving ice-sheets has been far from uniform upon the rocks exposed to it, this variation arising from the differences in powers of resistance of the rocks on the one hand, and in the mass, slope, and grinding power of the ice on the other. Over the lowlands, as in central Scotland and much of the north German plain, the rocks are for the most part concealed under glacial debris. But in the more undulating hilly ground, particularly in the north and north-west, the ice has effected the most extraordinary abrasion. It is hardly possible, indeed, to describe adequately in words these regions of most intense glaciation. The old gneiss of Norway and Sutherlandshire, for example, has been so eroded, smoothed, and polished, that it stands up in endless rounded hummocks, many of them still smooth and curved like dolphins' backs, with little pools, tarns, and larger lakes lying between them. Seen from a height the ground appears like a billowy sea of cold grey stone. The lakes, each lying in a hollow of erosion, seem scattered broadcast over the landscape. So enduring is the rock, that even after the lapse of so long an interval, it retains its ice-worn aspect almost as unimpaired as if the work of the glacier had been done only a few generations since.[1] The connection of the abundant ice-ground and lake-filled rock-basins of glaciated regions with the erosive work of land-ice was first pointed out by Sir Andrew C. Ramsay (p. 417). The phenomenon of "giants' kettles" (p. 415) is another mark of the same process of erosion.

Ice-crumpled Rocks.—Not only has the general surface of the land been abraded by the ice-sheets, but here and there more yielding portions of the rocks have been broken off or bent back, or corrugated by the pressure of the advancing ice. Huge blocks 200 yards or more in length, as in the case of the chalk erratics in the cliffs of Cromer, have been bodily displaced and launched forward on glacial detritus. The laminæ of shales or slates are observed to be pushed over or crumpled in the direction of ice-movement. Occasionally tongues of the glacial detritus which was simultaneously being pressed forward under the ice have been intruded into cracks in the strata, so as to resemble veins of eruptive rock.

Detritus of the Ice-sheet—Boulder-clay—Till—Older Diluvium.—Underneath the great ice-sheet, and perhaps largely incorporated in the lower portions of the ice, there accumulated a mass of earthy, sandy, and stony matter (till, boulder-clay, "grundmoräne," "moraine-profonde") which, pushed along and ground up, was the agent whereby the characteristic flowing outlines and smoothed striated surfaces were produced.[2] This "glacial drift"

[1] Some of these *roches moutonnées* are of Palæozoic age (*Nature*, August 1880).
[2] When the formation of the till began the materials may have consisted largely of a

spreads over the low ground of the glaciated districts and may even be traced up the valleys of the smaller groups of hills, whence it was not wholly removed by the erosion of the later glaciation. Thus it extends all over the low grounds of North Germany, Denmark, Holland, Scandinavia, Scotland, and much of England and Ireland, resting usually on surfaces of rock that have been worn smooth, disrupted, or crumpled by ice. It is not spread out, however, as a uniform sheet, but varies greatly in thickness and in irregularity of surface. Especially round the mountainous centres of dispersion it is apt to occur in long ridges or "drums," which run in the general direction of the rock-striation, that is, in the path of the ice-movement.

In those areas which served as independent centres of dispersion for the ice-sheet, the boulder-clay partakes largely of the local character of the rocks of each district where it occurs. Thus in Scotland the clay varies in colour and composition as it is traced from district to district. Over the Carboniferous rocks it is dark, over the Old Red Sandstones it is red, over the Silurian rocks it is fawn-coloured. The great majority of the stones, also, are of local origin, not always from the immediately adjacent rocks, but from points within a distance of a few miles. Evidence of transport can be gathered from the stones, for they are found in almost every case to include a proportion of fragments which have come from a distance. The direction of transport indicated by the percentage of travelled stones agrees with the traces of ice-movement as shown by the rock-striæ. Thus, in the lower part of the valley of the Firth of Forth, while most of the fragments are from the surrounding Carboniferous rocks, from 5 to 20 per cent. have come eastward from the Old Red Sandstone range of the Ochil Hills—a distance of 25 or 30 miles—while 2 to 5 per cent. are pieces of the Highland rocks, which must have come from high grounds at least 50 miles to the north-west. As each main mass of elevated ground seems to have caused the ice to move outward from it for a certain distance, until the stream coalesced with that descending from some other height, the bottom-moraine or boulder-clay, as it was pushed along, would doubtless take up local debris by the way, the detritus of each district becoming more and more ground up and mixed, until of the stones from remoter regions only a few harder fragments would be left. In cases where no prominent ridges interrupted the march of the ice-sheet, and where the ground was low and covered with soft loose deposits, blocks of hard crystalline rocks might continue to be recognizable far from their

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layer of decomposed rock due to prolonged pre-glacial disintegration (p. 338). It is difficult to explain by any known glacial operation the accumulation of such deep masses of detritus below a sheet of moving land-ice. Another problem is presented by the occasional and sometimes extensive preservation of undisturbed loose pre-glacial deposits under the till. The way in which the "Forest-bed" group has escaped for so wide a space under the Cromer cliffs, with their proofs of enormous ice-movement, is a remarkable example.

source. Thus in the stony clay and gravel of the plains of northern Germany and Holland, besides the abundant locally-derived detritus, fragments occur which have had an unquestionably northern origin. Some of the rocks of Scandinavia, Finland, and the Upper Baltic are of so distinctive a kind that they can be recognized in small pieces. Thus the peculiar syenite of Laurwig in the south of Norway has been recognized abundantly in the drift of Denmark; it occurs also in that of Hamburg, and has been detected even in the boulder-clay of the Holderness cliffs in Yorkshire. The well-known rhombenporphyr of southern Norway has likewise been recognized at Holderness. Fragments of the Silurian rocks from Gothland, or from the Russian islands Dago or Oesel, have been met with as far as the north of Holland. Pieces of granite, gneiss, various schists, porphyries, and other rocks, probably from the north of Europe, occur in the till of Norfolk.[1] These transported fragments are an impressive testimony to the movements of the northern ice. No Scandinavian blocks have been met with in Scotland, for the ice in that country was massive enough to move out into the basin of the North Sea (then doubtless in great part usurped by glaciers) until it met that which was streaming down from Scandinavia and thus kept it from bringing its freight of rock debris. But the Norwegian ice-sheet, which crept southwards across Denmark, once extended across the North Sea to the Yorkshire and Norfolk coasts, unless we suppose that the Scandinavian stones of Holderness and Cromer were carried on floating ice.

The stones in the boulder-clay have a characteristic form and surface. They are usually oblong, have one or more flat sides or "soles," are smoothed or polished, and have their edges worn round (Fig. 154). Where they consist of a fine-grained enduring rock, they are almost invariably found to be striated, the striæ running on the whole with the long axis of the stone, though one set of scratches may be seen crossing and partially effacing another, which would necessarily happen as the stones shifted their position under the ice. These markings are precisely similar to those on the solid rocks underneath the boulder-clay, and have manifestly been produced in the same way by the friction of stones and grains of sand as the whole mass of debris was being steadily pushed on in one general direction.

Interglacial Beds.—The boulder-clay is not one uniform mass of material. In a limited section, indeed, it usually appears as an unstratified mass of stiff stony clay. But it is found on further examination to be split up with various inconstant and local interstratifications, and in fact to consist of a group of deposits of different ages and formed under very various conditions. Beds of sand, gravel, fine clay, and peaty layers on different platforms in the boulder-clay, bear witness to intervals when the ice retired from the land, which, so

[1] These erratics from their petrographical characters appear to me to be certainly not from Scotland. Had that been their source they could not have failed to be accompanied by abundant fragments of the rocks of the south of Scotland, which are conspicuously absent.

far as uncovered, was eventually clothed with vegetation. Hence the long glacial period must have been interrupted by episodes, probably of considerable duration, when a milder climate prevailed. Such an alternation of conditions is explained on the hypothesis discussed in previous pages (pp. 21–29). During these intervals the Arctic mammals—the hairy mammoth, rhinoceros, rein-deer, musk-sheep, Arctic fox, glutton, and lemming—peopled the lower grounds. The mammoth advanced at least as far south as the now extinct volcanoes of central Italy, which were then in full activity. The rein-deer migrated southwards into Switzerland, the glutton into Auvergne, while the musk sheep and Arctic fox travelled certainly as far as the Pyrenees. When the climate became less chilly and allowed the animals of a more southern type to advance into Europe, the regions from which the Arctic foxes now retreated were visited by the porcupine, leopard, African lynx, lion, striped and spotted hyænas, African elephant, and hippopotamus.

Evidences of Submergence.—After the ice had attained its greatest development, some portions of north-western Europe which had perhaps stood at a higher level above the sea than they have done since, began to subside. The ice-fields were carried down below the sea-level, where they broke up and cumbered the sea with floating bergs. The heaps of loose debris which had gathered under the ice, being now exposed to waves, ground-swell, and marine currents, were thereby more or less washed down and reassorted. Coast-ice, no doubt, still formed along the shores, and was broken up into moving floes, as happens every year now in northern Greenland. The proofs of this phase of the long glacial period are contained in the sands, gravels, erratic blocks, and stratified clays which overlie the coarse older till. It is difficult to determine the extent of the submergence, for when the land rose the more elevated portions continued to be the seats of glaciers, which, moving over the surface, destroyed the deposits that would otherwise have remained as witnesses of the presence of the sea, while at the same time the great bodies of water discharged from the retreating glaciers and snow-fields must have done much to reassort the detritus on the surface of the land. The most satisfactory evidence of submersion is undoubtedly that supplied by beds of marine shells. From data of this kind we know that southern Scandinavia sank about 600 feet below its present level, while North Wales appears to have gone down at least 1350 feet.[1]

That ice continued to float about in these waters is shown by the striated stones contained in the fine clays, and by the remarkably contorted structure which these clays occasionally display. Sections may be seen (as at Cromer) where, upon perfectly undisturbed

[1] Mere fragments of marine shells in a glacial deposit need not prove submergence under the sea; for they may have been pushed up from the sea-floor by moving ice, as in the case of the shelly till of the west of Scotland, Caithness, Holderness, and Cromer. But beds of unbroken shells evidently assorted in water may be taken as good evidence of the former presence of the sea on their site.

horizontal strata of clay and sand, other similar strata have been violently crumpled, while horizontal beds lie directly upon them. These contortions may have been produced by the horizontal pressure of some heavy body moving upon the originally flat beds, such as ice in the form of an ice-sheet or of large stranding masses driven aground in the fjords or shallow waters where the clays accumulated, or possibly in some cases sheets of ice, laden with stones and earth, sank and were covered up with sand and clay, which, on the subsequent melting of the ice, would subside irregularly. Another indication of the presence of floating ice is furnished by large boulders scattered over the country, and lying sometimes on the stratified sands and gravels, though no doubt many of the so-called erratics belong to the time of the chief glaciation.

The sands and gravels which overlie the boulder-clay or older diluvium present some curious problems. Covering the lower ground in a sporadic manner, often tolerably thick on the plains, they rise up to heights of 1000 feet or more. In some places they cannot be satisfactorily separated from the sands and gravels associated with the boulder-clay, in others they seem to merge into the sandy deposits of the raised beaches, while in hilly tracts it is sometimes hard to distinguish between them and true moraine-stuff. Their most remarkable mode of occurrence is when they assume the form of mounds and ridges which run across valleys and plains, along hill-sides, and even over watersheds. Frequently these ridges coalesce so as to enclose basin-shaped hollows, which are often occupied by tarns. Many of the most marked ridges are not more than 50 or 60 feet in diameter, sloping up to the crest, which may be 20 or 30 feet above the plain. A single ridge may occasionally be traced in a slightly sinuous course for several miles. These ridges, known in Scotland as kames, in Ireland as eskers, and in Scandinavia as ösar, consist sometimes of coarse gravel or earthy detritus, but more usually of clean, well-stratified sand and gravel, the stratification towards the surface corresponding with the external slopes of the ground, in such a manner as to prove that the ridges are usually original forms of deposit, rather than the result of the irregular erosion of a general bed of sand and gravel. Some writers have compared these features to the submarine banks formed in the pathway of tidal currents near the shore. Others have supposed them rather to be of terrestrial origin, due to the melting of the great snow-fields and glaciers, and the consequent discharge of large quantities of water over the country. But no very satisfactory explanation of them has yet been given.

Second Glaciation—Re-elevation—Raised Beaches.—When the land re-emerged from its depression, the temperature all over central and northern Europe was again severe. Vast sheets of ice still held sway over the mountains, and continued to descend into the lower tracts and to go out to sea. To this period are ascribed certain terraces or "parallel-roads" which run along the sides of

valleys in the Scottish Highlands. It is believed that the mass of ice descending from some of the loftier snowfields of the time was so great as to accumulate in front of lateral valleys, and to so choke them up as to cause the water to accumulate in them and flow out in an opposite direction by the *col* at the head. In these natural reservoirs the level at which the water stood for a time was marked by a horizontal ledge or platform due partly to erosion of the hill-side and partly to the arrest of the descending debris when it entered the water.

Every group of mountains nourished its own glaciers; even small islands, such as Arran and Hoy in Scotland, had their snowfields, whence glaciers crept down into the valleys and shed their moraines. It would appear indeed that some of the northern glaciers of Scotland continued to reach the sea-level even when the land had risen to within 50 feet or less of its present elevation. On the east side of Sutherlandshire the moraines descend to the 50-feet raised beach; on the west side of the same county they come down still lower. The higher mountains of Europe still show the descendants of these later glaciers, but the ice has retreated from the lower elevations. In the Vosges the glaciers have long disappeared, but their moraines remain still fresh. In Wales, Cumberland, and the southern uplands and Highlands of Scotland, where moraines, perched blocks, and *roches moutonnées* attest the abundance and persistence of the last glaciers, it is possible to trace the stages of the gradual retreat of the ice towards its parent snow-fields, in the crescent-shaped moraine mounds that lie one behind another until they finally die out about the head of the valley, near what must have been the edge of the snow-field.

The uprise of the land in Scandinavia and Britain took place interruptedly. During its progress it was marked by long pauses when the level remained unchanged, when the waves and floating ice cut ledges along the sea-margin, and when sand and gravel were accumulated below high-water mark in sheltered parts of the coast-line. These platforms of erosion and deposit (raised beaches) form conspicuous features at successive heights above the present level of the sea (p. 277). The coast of Scotland is fringed by a succession of them. Those below the level of 100 feet above the sea are often remarkably fresh. The 100-feet terrace forms a wide plateau in the estuary of the Forth, and the 50-feet terrace is as conspicuous in that of the Clyde. In Scandinavia, especially in the northern parts of Norway, the successive pauses in the last uprise of the land are impressively revealed by long lines of terraces which wind around the hill-slopes that encircle the fjords (p. 279).

The records of the closing ages of the long and varied Glacial Period merge insensibly into those of later geological times. It is obvious that besides the effect of a general change of climate operating over the whole of the northern hemisphere, we must remember the influence which the natural features of different countries had upon the climate. From the plains the ice and snow would retire sooner than from the hills. In fact, we may regard some parts of Europe as

still retaining the conditions of the Glacial Period, though in diminished intensity. The present glaciers of the Alps are no doubt the lineal descendants of the vaster sheets that once descended into the lowlands on all sides from that central elevated region. And even where the ice has long since disappeared, there remain, in the living plants and animals of the higher and colder uplands, witnesses to the former severity of the climate. As that severity lessened, the Arctic vegetation that hitherto had peopled all the lower grounds of central and western Europe, was driven up into the hills before the advance of plants loving a milder temperature, which had doubtless been natives of Europe before the period of great cold, and which were now enabled to reoccupy the sites whence they had been banished. On the higher mountains, where the climate is still not wholly uncongenial for them, colonies of the once general Arctic flora still survive. The Arctic animals have also been mostly driven away to their northern homes, or have become wholly extinct.

It has been forcibly pointed out by Mr. Wallace that the present mammalian fauna of the globe presents everywhere a striking contrast to the extraordinary variety and great size of the mammals of the Tertiary periods. "We live," he says, "in a zoologically impoverished world, from which all the largest, and fiercest, and strangest forms have recently disappeared."[1] He connects this remarkable reduction with the refrigeration of climate during the Glacial Period. The change, to whatever cause it may be assigned, is certainly remarkably persistent in the Old World and in the New, and not merely in the temperate and northern regions, but even as far south as the southern slopes of the Himalaya Mountains.

§ 2. Local Development.

Britain.—Though the generalized succession of phenomena above given is usually observable, some variety is traceable in the evidence in different parts of the British area. In Scotland, where the ground is generally more elevated, and where snow and ice were most abundant, the phenomena of glaciation reached their maximum development. In the high grounds of England, Wales, and Ireland there was likewise extensive accumulation of ice. The ice-worn rocks of the low grounds are usually covered by boulder-clay, which in Scotland is interstratified with beds of sand, fine clay, and peat, marking interglacial terrestrial periods, but has never yielded any marine organisms except near the coast, where they are sometimes common, and in one locality in Lanarkshire. In England, marine shells, usually fragmentary, occur in the boulder-clays both in the eastern and western counties. The ice-sheet no doubt passed over some parts of the sea-bottom, and ground up the shell-banks that happened to lie in its way, as has happened, for example, in Caithness, Holderness, and East Anglia, where the shells in the boulder-clay are fragmentary, and sometimes ice-striated. The "Bridlington Crag" of Yorkshire is regarded by Mr. C. Reid as a large

[1] *Geographical Distribution of Animals*, i. p. 150.

fragment torn from a submarine shell-clay, and imbedded in the boulder-clay. With the exception of such marine enclosures the organic contents as well as the physical characters of the Scottish till point to terrestrial conditions of deposit under the ice-sheet.

The records of the submersion of Britain are probably very incomplete. If we rely only on the evidence of actual marine shells we obtain the lowest limit of depression. But the renewed ice and snow, after re-elevation, may well have destroyed most of the shell-beds, and their destruction would be most complete where the snowfields and glaciers were most extensive. Beds of sand and gravel with recent shells have been observed on Moel Tryfaen, in North Wales, at a height of no less than 1350 feet, but as the same kind of deposits in which they occur extend to a much greater height, the submergence may have considerably exceeded the limit at which the shells occur. In Cheshire beds of shells have been met with at a height of 1200 feet. In Scotland the highest

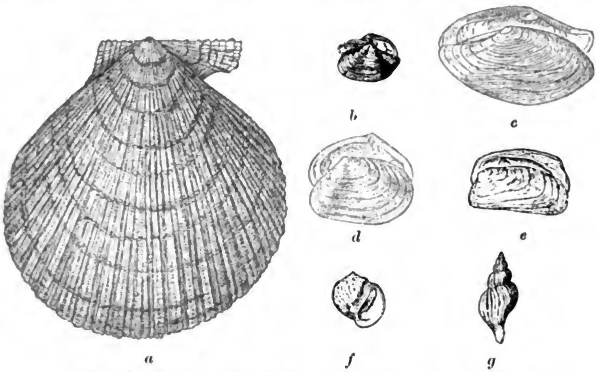

FIG. 426. GROUP OF SHELLS FROM THE SCOTTISH GLACIAL BEDS.

a, Pecten islandicus (Müll.) (½); *b*, Leda truncata (Brown) (½); *c*, Leda lanceolata (Sow.) (Yoldia arctica, Müll.) (½); *d*, Tellina lata (Gmelin) (T. calcarea, Wahl.) (½); *e*, Saxicava rugosa (Pennant) (½); *f*, Natica clausa (Brod. and Sow.) (½); *g*, Trophon scalariforme (Gould) (T. clathratum) (½).

level from which they have yet been obtained is 524 feet, in one of the interstratifications in the boulder-clay at the Lanarkshire locality just referred to. Subsequent elevation of the land has brought up within tide-marks some of the clays deposited over the sea-floor during the time of the submergence. In the Clyde basin and some of the western fjords these clays (Clyde beds) are full of shells. Comparing the species with those of the adjacent seas, we find them to be more boreal in character; nearly the whole of the species still live in Scottish seas, though a few are extremely rare. Some of the more characteristic northern shells in these deposits are *Pecten islandicus*, *Tellina lata* (*T. calcarea*), *Leda truncata*, *L. lanceolata* (*Yoldia arctica*), *Saxicava rugosa*, *Panopæa norvegica*, *Trophon scalariforme* (*T. clathratum*), and *Natica clausa* (Fig. 426).

In the later stages of the Glacial Period the records are much the same all over Britain, allowance being made for the greater cold and longer lingering of the glaciers in the north than in the south, and among the hills than on the plains.

In Scotland the following may be taken as the average succession of glacial phenomena in descending order:

Last traces of glaciers, small moraines at the foot of corries among the higher mountain groups.
Marine terraces (50 feet and higher). Clay-beds of the Arctic sea-bottom (Clyde beds) containing northern molluscs.
Large moraines coming down even to the 50-feet raised beach, showing that the glaciers of the second period descended to the sea-level in some places.
Erratic blocks. These were partly transported by the first ice-sheet, partly by the later glaciers, and partly by floating ice during the period of submergence.
Sands and gravels—Kame or Esker series, sometimes containing terrestrial organisms, sometimes marine shells.
Upper boulder-clays—rudely stratified clays with sands and gravels.
Till or lower boulder-clay (bottom moraine of the ice-sheet)—a stiff stony unstratified clay, varying up to 100 feet or more in thickness. It contains intercalated bands of fine sand, finely laminated clays, layers of peat and terrestrial vegetation, and bones of mammoth and reindeer (inter-glacial beds), also in some places fragments of Arctic and boreal marine shells, in other places less fragmentary assemblages of similar shells, which prove a submergence of at least 524 feet below the present level of the sea. The boulder-clay spreads over the lower grounds, often taking the form of parallel ridges or drums.
Ice-worn rock surfaces.

Over a great part of England and Ireland the drift deposits are capable of subdivision, as follows:

4. Moraines and raised beaches.
3. Upper boulder-clay—a stiff stony clay with ice-worn stones and intercalations of sand, gravel, or silt. It has a more sandy and less unstratified aspect than the lower boulder-clay, and occasionally contains marine shells.
2. Middle sands and gravels, containing marine shells. At Macclesfield (1200 feet above the sea) the species include *Cytherea chione*, *Cardium rusticum*, *Arca lactea*, *Tellina balthica*, *Cyprina islandica*, *Astarte arctica*, and other shells now living in the seas around Britain, but indicating perhaps by their grouping a rather colder climate than the present. At Moel Tryfaen near Caermarthen a similar assemblage of shells has been met with at 1350 feet above the sea. Near Yarmouth the middle glacial beds have yielded shells of a more southern aspect. In Ireland also the middle sands and gravels have furnished marine shells of living British species at heights of 1300 feet above the sea.
1. Lower boulder-clay—a stiff clayey deposit stuck full of ice-worn blocks, and equivalent to the till of Scotland. On the east coast of England it contains fragments of Scandinavian rocks. Along the Norfolk cliffs it presents stratified intercalations with bands of gravel and sand, which have been extraordinarily contorted. As in Scotland the true lower boulder-clay in the north of England and Ireland is often arranged in parallel ridges or drums in the prevalent line of ice-movement. As above mentioned the so-called "crag" of Bridlington, Yorkshire, is probably a fragment of an old marine glacial shell-bearing clay, which has been torn up and imbedded in the boulder-clay of the first ice-sheet.

Scandinavia.—The order of Pleistocene phenomena is generally the same here as in Britain. The surface of the country has been everywhere intensely glaciated, and the ice-striæ show that the great ice-sheet

moved outwards from the axis of the peninsula down the western fjords into the Atlantic, and southwards and south-eastwards into the Baltic. The march of the ice is likewise well marked by the dispersion of the erratic blocks. The subsequent partial submergence of the country is proved by numerous shell-bearing clays. The fossils in the higher littoral shell-beds indicate a more Arctic climate; they include, as in the Scottish glacial clays, great numbers of thick-shelled varieties of *Mya truncata* and *Saxicava rugosa*; also *Balanus porcatus*, *B. crenatus*, *Mytilus edulis*, *Pecten islandicus*, *Buccinum grœnlandicum*, *Trophon scalariforme* (*T. clathratum*), *Natica clausa*. The clays of deeper water contain *Leda lanceolata* (*Yoldia arctica*), *Yoldia intermedia*, *Y. pygmæa*, *Dentalium abyssorum*, &c. The fossiliferous deposits of lower levels point to a climate more nearly approaching the present, for the more thoroughly Arctic species disappear, and the thick-shelled varieties of *Mya* and *Saxicava* pass into the usual thin-shelled kinds. The remarkable terraces that fringe the coast of Norway from the southern or Christiania region to the North Cape mark pauses in the re-elevation of the land. The eastern plains of Sweden and the lower grounds of southern Norway are marked by great accumulations of sand and gravel (ösar) like the kames of Scotland and the eskers of Ireland.

Germany.—Since the year 1878 an active exploration of the earlier memorials of the glacial period has been carried on in northern Germany, with the result of bringing out more clearly the evidence for the prolongation of the Scandinavian and Finland ice across the Baltic and the plains of Germany even into Saxony. The limits reached by the ice are approximately fixed by the line to which northern erratics can be traced. Above the glaciated rocks comes a stiff, unstratified clay, with ice-striated blocks of northern origin—the till or boulder-clay. Traces of submergence are indicated by overlying beds containing *Tellina solidula*, *Cyprina islandica*, *Cardium edule*, &c., while some of the lakes which occupied hollows in the drift when the ice retired are indicated by stratified deposits with *Paludina diluviana*, &c.

In southern Germany representatives of the boulder-clay occur in those regions which lay within the area overspread by the glaciers of the Alps and other high grounds. Elsewhere Pleistocene deposits consist of river-terraces, loess, cave-earth, cave-breccia, and peat. A wide area of the lower plains of the Danube, extending into the Carpathians and Transylvania, is covered with loess. The fine calcareous loam known by this name attains also a great development in the valley of the Rhine, where it has been long known and studied, especially between Basel and Mayence, rising in some places to 800 feet above the level of the river, occupying tributary valleys and even spreading over the adjoining table-land. The same deposit is traceable below the gorge of the Rhine, spreading out over the low grounds and merging into the Hesbayan mud of Belgium (p. 887), which extends to near Dunkirk on the French coast. This great accumulation of fine detritus is not well stratified, and has sufficient coherence to form perpendicular bluffs. It has been regarded as due to the deposit of glacial mud during the more rapid melting of the great Alpine glaciers towards the close of the Ice Age, but it bears some traces of a subaerial origin (pp. 322, 384). Though on the whole unfossiliferous, it contains sometimes numerous land-shells of the same species as still inhabit the Rhine valley

(*Succinea oblonga*, *Pupa muscorum*, *Helix hispida*), together with bones of recent and extinct mammals. A similar deposit occupies a wide area in the valley of the Danube, and occurs also in that of the Meuse. The occurrence of traces of man in association with remains of extinct mammals in the loess was claimed by Ami Boué many years ago. Other confirmatory observations of later years seem to have established the fact.

France.—In France the true till or boulder-clay appears to be absent, as it is also from the south of England. The older Pleistocene deposits (perhaps interglacial) consist of fluviatile gravels and clays which, in their composition, belong to the drainage systems in which they occur. There is no evidence of transport from a distance. The rivers, however, were probably much larger than they now are during some part of the Pleistocene period. They have left their ancient platforms of alluvium high above the present watercourses. In the Paris basin the Pleistocene beds are grouped in descending order as follows:

Red Diluvium—red or grey clays with flints and angular pebbles, sometimes exhibiting contorted stratification. These clays, probably of different ages, are found on the higher river terraces as well as on the slopes and lower levels. They possibly belong to the period of the second glaciation.

Grey Diluvium, gravelly diluvium—grey or red coarse river-gravels, perhaps inter-glacial, with numerous organic remains, including many terrestrial and fresh-water shells, most of which are of still living species, and numerous mammalian bones, among which are *Rhinoceros tichorhinus*, *R. etruscus*, *R. leptorhinus*, *Hippopotamus major*, *Elephas antiquus*, *E. primigenius*, wild boar, stag, roe, ibex, Canadian elk, musk-sheep, urus, beaver, cave-bear, wolf, fox, cave-hyæna, and cave-lion. Palæolithic implements show that man was a contemporary of these animals.

Belgium.—The Quaternary deposits of this country, like those of France, belong to a former condition of the present river basins. In the higher tracts they are confined to the valleys, but over the plains they spread as more or less continuous sheets. Thus, in the valley of the Meuse, the gravel terraces of older diluvium on either side bear witness only to transport within the drainage basin of the river, though fragments of the rocks of the far Vosges may be detected in them. The gravels are stratified, and are generally accompanied by an upper sandy clay. In middle Belgium the lower diluvial gravels are covered by a yellow clay or mud (Hesbayan), probably a continuation of the German loess, with numerous terrestrial shells (*Succinea oblonga*, *Pupa muscorum*, *Helix hispida*). In lower Belgium this clay is replaced by the Campinian sands. The Belgian caverns and some parts of the diluvium have yielded a large number of mammalian remains, among which there is the same commingling of types from cold and from warm latitudes so observable in the Pleistocene beds of England and France. Thus the Arctic reindeer and glutton are found with the Alpine chamois and marmot, and with the lion and grizzly bear.

Switzerland.—The successive stages of the glacial period have been arranged as under:

Post-glacial. Ancient lacustrine terraces (150 feet above present level of Lake of Geneva), deltas, and river gravels with *Limnæa stagnalis* and other fresh-water shells, bones of mammoth (?).

Second extension of the glaciers. Erratic blocks and terminal moraines of Zurich, Baldegg, Sempach, Bern, with an Arctic flora and fauna.

Inter-glacial beds. Gravels, lignites, and clays of Utznach, Dürnten, &c., covered by the moraine stuff of the second glaciation and overlying the oldest glacial deposits—*Elephas antiquus, Rhinoceros leptorhinus.*
First glaciation. Striated blocks found under the inter-glacial beds.

North America.—The general succession of events in post-Tertiary times appears to have been nearly the same over the northern hemisphere both in the New and the Old World. In North America we have the same sharply-defined line between the older post-Tertiary deposits and previous formations, due to the glacial conditions which, overspreading these regions, in great measure destroyed the superficial accumulations of the immediately preceding eras. The Quaternary or post-Tertiary formations are grouped by American geologists in the following subdivisions:

3. Recent and Prehistoric	Peat, alluvium, blown sand, "alkali" deposits, geyser deposits, cave deposits, artificial mounds.
2. Champlain	River-, lake-, and sea-terraces, loess. *Saxicava* sand, Champlain clays, *Leda* clay.
1. Glacial	Boulder-clays, unstratified clays, sands, and gravels.

1. *Glacial.*—As in northern Europe, the rocks underneath the glacial deposits of North America are well ice-worn. The direction of the striæ is generally southward, varying to south-east and south-west according to the form of the ground. The great thickness of the ice-sheet is strikingly shown by the height to which some of the higher elevations are polished and striated. Thus the Catskill Mountains rising from the broad plain of the Hudson have been ground smooth and striated up to near their summits, or about 3000 feet, so that the ice must have been of even greater thickness than that. The White Mountains are ice-worn even at a height of 5500 feet. As in Europe, the glacial deposits increase in thickness and variety from south to north. The southern limit of the unstratified drift lies somewhere in the neighbourhood of the 39th parallel of north latitude, and the deposit ranges from the Atlantic westward to the meridian of 98°. It spreads, therefore, across Canada, and is found over a considerable area of the north-eastern States. It rises to a height of 5800 feet among the White Mountains. The absence of any true boulder-drift on the Rocky Mountain slopes, where it might have been looked for, is remarkable, for these mountains once nourished large glaciers, which have left enormous piles of moraine stuff, and have strewn many hills with transported erratic blocks. There is likewise a tract south-west from Lake Michigan which has escaped the ice-sheets that elsewhere have covered the eastern parts of the States with detritus. The coarse unstratified drift or boulder-clay bears witness to a general southerly transport of material, and, in conjunction with the striated rocks, shows that the great ice-sheet moved from north to south at least as far as about the latitude of Washington. Logan mentions that in some parts of Canada the glacial drift and boulders run in ridges north and south, thus corresponding with the general direction of transport, like the "drums" in Britain. As in Europe, the coarse boulder-clay at the base is essentially unfossiliferous.

2. *Champlain.*—Under this name have been classed the loose deposits or drifts overlying the lower unstratified boulder-clay, and belonging to the period of the melting of the great ice-sheets, when large bodies of

water, discharged across the land, levelled down the heaps of detritus that had formed below or in the under part of the ice. The lower portions of the Champlain series are, therefore, sometimes unstratified or very rudely stratified, while the upper parts are more or less perfectly stratified. Towards the eastern coasts, and along the valleys penetrating from the sea into the land, these stratified beds are of marine origin, and prove that during the Champlain period there was a depression of the eastern part of Canada and the United States beneath the sea, increasing in amount northwards from a few feet in the south of New England to more than 500 feet in Labrador. The marine accumulations are well developed in eastern Canada, where they show the following subdivisions:

Upper.	St. Maurice and Sorel sands; *Saxicava* sand of Montreal; upper sand and gravel of Beauport; upper Champlain clay and sand of Vermont.
Lower.	*Leda* clay of the St. Lawrence and Ottawa; lower shell-sand of Beauport; lower Champlain clay of Vermont.

The lower stage, chiefly clays, which rise to a height of 600 feet above the sea, includes some interstratified beds of siliceous sand, but few boulders. It contains marine organisms, such as *Leda truncata*, *Saxicava rugosa*, *Tellina grœnlandica*, bones of seals, whales, &c. On the banks of the Ottawa, in Gloucester, the clays contain numerous nodules which have been formed round organic bodies, particularly the fish *Mallotus villosus* or capeling of the lower St. Lawrence. Dawson also obtained numerous remains of terrestrial marsh plants, grasses, carices, mosses, and algæ. This writer states that about 100 species of marine invertebrates have been obtained from the clays of the St. Lawrence valley. All except four or five species in the older part of the deposits are shells of the boreal or Arctic regions of the Atlantic; and about half are found also in the glacial clays of Britain. The great majority are now living in the Gulf of St. Lawrence and on neighbouring coasts, especially off Labrador.[1]

Terraces of marine origin occur both on the coast and far inland. On the coast of Maine they appear at heights of 150 to 200 feet, round Lake Champlain at least as high as 300 feet, and at Montreal nearly 500 feet above the present level of the sea. In the absence of organic remains, however, it is not always possible to distinguish between terraces of marine origin marking former sea-margins, and those left by the retirement of rivers and lakes. In the Bay of Fundy evidence has been cited by Dawson to prove subsidence, for he has observed there a submerged forest of pine and beech lying 25 feet below high-water mark.[2]

Inland the stratified parts of the Champlain series have been accumulated on the sides of rivers, and present in great perfection the terrace character already (p. 382) described. The successive platforms or terraces mark the diminution of the streams. They may be connected also with an intermittent uprise of the land, and are thus analogous to sea-terraces or raised beaches. Each uplift that increased the declivity of the rivers would augment their rate of flow, and consequently their scour, so that they would be unable to reach their old flood-plains. Such evidences of diminution are almost universal among

[1] Dawson, *Acadian Geology*, p. 76.
[2] *Op. cit.* p. 28.

the valleys in the drift-covered parts of North America, as in the similar regions of Europe. Sometimes four or five platforms, the highest being a hundred feet or more above the present level of the sea, may be seen rising above each other, as in the well-known example of the Connecticut Valley.

The terraces are not, however, confined to river-valleys, but may be traced round many lakes. Thus in the basin of Lake Huron deposits of fine sand and clay containing fresh-water shells rise to a height of 40 feet or more above the present level of the water, and run back from the shore sometimes for 20 miles. Regular terraces, corresponding to former water-levels of the lake, run for miles along the shores at heights of 120, 150, and 200 feet. Shingle beaches and mounds or ridges, exactly like those now in course of formation along the exposed shores of Lake Huron, can be recognized at heights of 60, 70, and 100 feet. Unfossiliferous terraces occur abundantly on the margin of Lake Superior. At one point mentioned by Logan, no fewer than seven of these ancient beaches occur at intervals up to a height of 331 feet above the present level of the lake.[1] The great abundance of terraces of fluviatile, lacustrine, and marine origin led, as already stated, to the use of the term "Terrace Epoch" as the designation of the time when these remarkable topographical features were produced.

India.—There is abundant evidence that at a late geological period glaciers descended from the southern slopes of the Himalaya Mountains to a height of less than 3000 feet above the present sea-level. Large moraines are found in many valleys of Sikkim and Eastern Nepal between 7000 and 8000 feet, and even down to 5000 feet, above sea-level. In the Western Himalayas perched blocks are found at 3000 feet, and in the Upper Punjaub very large erratics have been observed at still lower elevations. No traces of glaciation have been detected in Southern India. Besides the physical evidence of refrigeration, the present facies and distribution of the flora and fauna on the south side of the Himalaya chain suggest the influence of a former cold period.[2]

New Zealand.—The present glaciers of the New Zealand Alps had a much greater extension at a recent geological period. According to Dr. Haast they descended into the plains, and, on the west side of the island, probably advanced into the sea, for along that coast-line their moraines now reach the sea-margin; huge erratics stand up among the waves, and the surf breaks far outside the shore-line, probably upon a seaward extension of the moraines.[3] Captain Hutton, however, points out that there is no evidence from the fauna of any general and serious refrigeration of the climate during this glacier period.[4]

Section II.—Recent or Human Period.

§ 1. General Characters.

The long succession of Pleistocene ages shaded without abrupt change of any kind into what is termed the Human or Recent

[1] *Geology of Canada*, p. 910.
[2] Medlicott and Blanford, *Geology of India*, p. 586.
[3] *Geology of Canterbury and Westland*, p. 371.
[4] *Geology of Otago*, p. 83.

Period.[1] The Ice Age, or Glacial Period may indeed be said still to exist in Europe. The snow-fields and glaciers have disappeared from Britain, France, the Vosges, and the Harz, but they still linger among the Pyrenees, remain in larger mass among the Alps, and spread over wide areas in northern Scandinavia. This dovetailing or overlapping of geological periods has been the rule from the beginning of time, the apparently abrupt transitions in the geological record being due to imperfections in the chronicle.

The last of the long series of geological periods may be subdivided into subordinate sections as follows :

Historic, up to the present time.

Prehistoric $\begin{cases} \text{Iron, Bronze, and later Stone.} \\ \text{Neolithic.} \\ \text{Palæolithic.} \end{cases}$

The Human Period is above all distinguished by the presence and influence of man. It is difficult to determine how far back the limit of the period should be placed. The question has often been asked whether man was coeval with the Ice Age. To give an answer, we must know within what limits the term Ice Age is used, and to what particular country or district the question refers. For it is evident that even to-day man is contemporary with the Ice Age in the Alpine valleys and in Finmark. There can be no doubt that he inhabited Europe after the greatest extension of the ice. He not improbably migrated with the animals that came from warmer climates into this continent during the interglacial intervals. But that he remained when the climate again became cold enough to freeze the rivers and permit an Arctic fauna to roam far south into Europe is proved by the abundance of his flint implements in the thick river-gravels, into which they no doubt often fell through holes in the ice as he was fishing.

The proofs of the existence of man in former geological periods are not to be sought for in the occurrence of his own bodily remains, as in the case of other animals. His bones are indeed now and then to be found, but in the vast majority of cases his former presence is revealed by the implements he has left behind him, formed of stone, metal, or bone. Many years ago the archæologists of Denmark, adopting the subdivisions of the Latin poets, classified the early traces of man in three great divisions—the Stone Age, Bronze Age, and Iron Age. There can be no doubt that, on the whole, this has been the general order of succession in Europe, where men used stone and bone before they had discovered the use of metal, and learnt how to obtain bronze before they knew anything of the metallurgy of iron. Nevertheless, the use of stone long survived the introduction of bronze and iron. In fact, in many European countries where metal has been known for many centuries, there are districts where stone implements are still employed, or where they

[1] See for general information Lyell's *Antiquity of Man*, Lubbock's *Prehistoric Times*, Evans' *Ancient Stone Implements*, Boyd Dawkins' *Cave Hunting* and *Early Man in Britain*, J. Geikie's *Prehistoric Europe*.

were in use until quite recently. It is obvious also that, as there are still barbarous tribes unacquainted with the fabrication of metal, the Stone Age is not yet extinct in some parts of the world. In this instance we again see how geological periods run into each other. The nature or shape of the implement cannot therefore be always a very satisfactory proof of antiquity. We must judge of it by the circumstances under which it was found. From the fact that in north-western Europe the ruder kind of stone weapons occurs in what are certainly the older deposits, while others of more highly finished workmanship are found in later accumulations, the Stone Age has been subdivided into an early or Palæolithic and a later or Neolithic epoch. There can be no doubt, however, that the latter was

FIG. 427.—PALÆOLITHIC FLINT IMPLEMENT.

in great measure coeval with the age of bronze, and even to some extent of iron.[1]

The deposits which contain the history of the Human Period are cavern-loam, brick-earth, river-alluvia, lake-bottoms, peat-mosses, sand-dunes, loess, and other superficial accumulations.

PALÆOLITHIC.—Under this term are included those deposits which have yielded rudely-worked flints of human workmanship associated with the remains of mammalia, some of which are extinct, while others no longer live where their remains have been obtained. An association of the same mammalian remains under similar conditions, but without traces of man, may be assigned to the same geological

[1] The student may profitably consult Dr. Arthur Mitchell's *Past in the Present*, 1880, for the warnings it contains as to the danger of deciding upon the antiquity of an implement merely from its rudeness.

period, and be included in the Palæolithic series. A satisfactory chronological classification of the deposits containing the first relics of man is perhaps unattainable, for these deposits occur in detached areas with no means of determining their physical sequence. To assert that a brick-earth is older than a cavern-breccia, because it contains some bones which the latter does not, or fails to show some which the latter does yield, is too often a conclusion drawn because it agrees with preconceptions.

River-Alluvia.—Above the present levels of the rivers there lie platforms or terraces of alluvium, sometimes to a height of 80 or 100 feet. These deposits are fragments of the river-gravels and loams laid down when the streams flowed at that elevation, and therefore before the valleys were widened and deepened to their present form. River-action is at the best but slow. To erode the valleys to so great a depth beneath the level of the upper alluvia, must have demanded a period of many centuries. There can therefore be no doubt of the high antiquity of these deposits. They have yielded the remains of many mammals, some of them extinct, together with the flint flakes made by man. From the nature and structure of some of the high-lying gravels there can be little doubt that they were formed at a time when the rivers, then larger than now, were liable to be frozen and to be obstructed by large accumulations of ice. We are thus able to connect the deposits of the Human Period with some of the later phases of the Ice Age in the west of Europe.

Brick Earths.—In some regions that have not been below the sea for a long period a variable accumulation of loam has formed on the surface from the decomposition of the rocks *in situ* aided by the drifting of fine particles by wind and the gentle washing action of rain and occasionally of streams. Some of these brick-earths or loams are of high antiquity, for they have been buried under fluviatile deposits, which must have been laid down when the rivers flowed far above their present levels. They have yielded traces of man associated with bones of extinct mammals.

Cavern Deposits.—Most calcareous districts abound in underground tunnels and caverns which have been dissolved by the passage of water from the surface (p. 355). Where these cavities have communicated with the outer surface, terrestrial animals, including man himself, have made use of them as places of retreat, or have fallen or been washed into them. The floors of some of them are covered with a reddish or brownish loam or cave-earth, resulting either from the insoluble residue of the rock left behind by the water that dissolved out the caverns, or from the deposit of the silt carried in the water which in some cases has certainly flowed through them. Very commonly a deposit of stalagmite has formed from the drip of the roof above the cave-earth. Hence any organic remains which may have found their way to these floors have been sealed up and admirably preserved.

The fauna found in Palæolithic deposits is remarkable for a mixture of forms from warmer and colder latitudes similar to that already noted among the interglacial beds. It has been inferred,

Fig. 428.—Figure of the Mammoth.
Engraved on ivory by Cave-men, La Madelaine, France (Lartet, *Reliquiæ Aquitan.*).

indeed, that the Palæolithic gravels are themselves referable to interglacial conditions. On the one hand, we meet with a number of living species of warmer habitat, as the lion, hyæna, hippo-

potamus, lynx, leopard, and caffer cat; but, on the other hand, the great majority of the forms are northern, such as the glutton, Arctic fox, reindeer, Norwegian lemming, Arctic lemming, marmot, and musk-sheep. With these are associated a number of extinct forms, including the Irish elk, *Elephas primigenius* or mammoth, *E. antiquus*, *Rhinoceros megarhinus*, *R. tichorhinus*, *R. leptorhinus*, and cave-bear. That man was the contemporary of these animals is proved by the frequent occurrence of undoubtedly human implements formed of roughly chipped flints, &c., associated with their bones. Much more rarely portions of human skeletons have been recovered from the same deposits. The men of the time appear to have camped in rock-shelters and caves, and to have lived by fishing

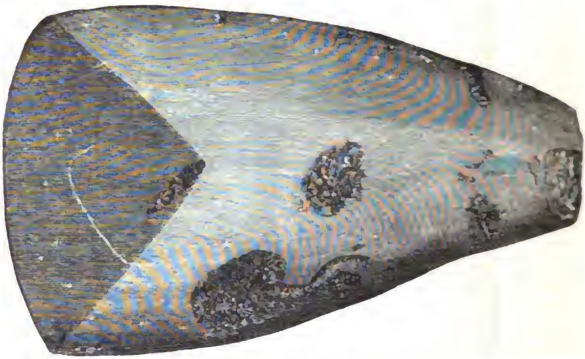

Fig. 429.—Neolithic Stone Implement.

and by hunting the reindeer, bison, horse, mammoth, rhinoceros, cave-bear, and other animals. That they were not without some kind of culture is shown by the vigorous incised sketches and carvings which they have left behind on reindeer antlers, mammoth tusks, and other bones, depicting the animals with which they were daily familiar. Some of these drawings are especially valuable as they represent forms of life long ago extinct, such as the mammoth and cave-bear. The men who in Palæolithic time inhabited the caves of Europe must have had much similarity if not actual kinship to the modern Eskimos.

Neolithic.—The deposits whence the history of Neolithic man is compiled must vary widely in age. Some of them were no doubt contemporaneous with parts of the Palæolithic series, others with the Bronze and Iron series. They consist of cavern deposits, alluvial accumulations, peat-mosses, lake-bottoms, pile-dwellings, and shell-mounds.

The list of mammals, &c., inhabiting Europe during Neolithic is distinguished from that of Palæolithic time by the absence of the mammoth, woolly rhinoceros, and other extinct types, which appear to have meanwhile died out in Europe. The only form now extinct which appears to have survived into Neolithic time was the Irish elk. The general assemblage of animals was probably much what it has been during the period of history, but with a few forms which have disappeared from most of Europe either within or shortly before the historic period, such as the reindeer, elk, urus, grizzly bear, brown bear, wolf, wild boar, and beaver. But besides these wild animals there are remains of domesticated forms introduced by the race which supplanted the Palæolithic tribes. These are the dog, horse, sheep, goat, shorthorn, and hog. It is noteworthy that these domestic forms were not parts of the indigenous fauna of Europe. They appear at once in the Neolithic deposits, leading to the inference that they were introduced by the human tribes which now migrated, probably from Central Asia, into the European continent. These tribes were likewise acquainted with agriculture, for several kinds of grain, as well as seeds of fruits, have been found in their lake-dwellings; and the deduction has been drawn from these remains that the plants must have been brought from southern Europe or Asia. The arts of spinning, weaving, and pottery-making were also known to these people. Human skeletons and bones belonging to this age have been met with abundantly in barrows and peat-mosses, and indicate that Neolithic man was of small stature, with a long or oval skull.

The history of the Bronze and Iron Ages in Europe is told in great fulness, but belongs more fittingly to the domain of the archæologist, who claims as his proper field of research the history of man upon the globe. The remains from which the record of these ages is compiled are objects of human manufacture, graves, cairns, sculptured stones, &c., and their relative dates have in most cases to be decided, not upon geological, but upon archæological grounds. When the sequence of human relics can be shown by the order in which they have been successively entombed, the inquiry is strictly geological, and the reasoning is as logical and trustworthy as in the case of any other kind of fossils. Where, on the other hand, as so often happens, the question of antiquity has to be decided solely by relative finish and artistic character of workmanship, it must be left to the experienced antiquary.

§ 2. Local Development.

A few examples of the nature of the deposits of the Palæolithic and Neolithic series will suffice to show their general nature.

Britain.—Palæolithic deposits are absent from the north of England and from Scotland. They occur in the south of England, and notably in the valley of the Thames. In that district a series of brick-earths with intercalated bands of river-gravel, having a united thickness of more

than 25 feet, is overlaid by a remarkable bed of clay, loam, and gravel ("loess" or "trail"), three feet or more in thickness, which in its contorted bedding and large angular blocks probably bears witness to its having been accumulated during a time of floating ice. The strata below the glacial deposit have yielded a remarkable number of mammalian bones, among which have been found undoubted human implements of chipped flint. The number of species amounts to 26, which include *Rhinoceros leptorhinus*, *R. tichorhinus*, *R. megarhinus*, *Elephas antiquus*, *E. primigenius*, *Megaceros Hibernicus*, *Felis leo*, *Hyæna crocuta*, *Ursus ferox*, *U. arctos*, *Ovibos moschatus*, *Hippopotamus major*, and present another example of the mingling of northern with southern, and of extinct with still living forms, as well as of species which have long disappeared from Britain with others still indigenous. Other ancient alluvia, far above the present levels of the rivers, have likewise furnished similar evidence that man continued to be the contemporary in England of the northern rhinoceros and mammoth, the reindeer, grizzly bear, brown bear, Irish elk, hippopotamus, lion, and hyæna.

The caverns in the Devonian, Carboniferous, and Magnesian limestones of England have yielded abundant relics of the same prehistoric fauna, with associated traces of Palæolithic man. In some of these places the lowest deposit on the floor contains rude flint implements of the same type as those found in the oldest river-gravels, while others of a more finished kind occur in overlying deposits, whence the inference has been drawn that the caverns were first tenanted by a savage race of extreme rudeness, and afterwards by men who had made some advance in the arts of life. The association of bones shows that when man had for a time retired, some of these caves became hyæna-dens. Hyæna bones in great numbers have been found in them, with abundant gnawed bones of other animals on which the hyænas preyed. Holes in the limestone opening to the surface (sinks, swallow-holes) have likewise become receptacles for the remains of many generations of animals which fell into them by accident, or crawled into them to die. In a fissure of the limestone near Castleton, Derbyshire, from a space measuring only 25 by 18 feet, no fewer than 6800 bones, teeth, or fragments of bone were obtained, chiefly bison and reindeer, with bears, wolves, foxes, and hares.[1]

France.—It was in the valley of the Somme, near Abbeville, that the first observations were made which led the way to the recognition of the high antiquity of man upon the earth. That valley has been eroded out of the chalk, which rises to a height of from 200 to 300 feet above the modern river. Along its sides, far above the present alluvial plain, are ancient terraces of gravel and loam, formed at a time when the river flowed at higher levels. The lower terrace of gravel, with a covering of flood-loam, ranges from 20 to 40 feet thick, while the higher bed is about 30 feet. Since their formation the Somme has eroded its channel down to its present bottom, and may have also diminished in volume, while the terraces have, during the interval, here and there suffered from denudation. Flint implements have been obtained from both terraces, and in great numbers, associated with bones of mammoth, rhinoceros, and other extinct mammals (p. 898).

The caverns of the Dordogne and other regions in the south of France have yielded abundant and varied evidence of the coexistence of man

[1] Boyd Dawkins, *Early Man in Britain*, p. 188.

with the reindeer and other animals either wholly extinct or no longer indigenous. So numerous in particular are the reindeer remains, and so intimate the association of traces of man with them, that the term "Reindeer period" has been proposed for the section of prehistoric time to which these interesting relics belong. The art displayed in the implements found in the caverns has been supposed to indicate a considerable advance on that of the chipped flints of the Somme. Some of the pictures of reindeer and mammoths, incised on bones of these animals, are singularly spirited (Fig. 428).

Switzerland.—The lakes of Switzerland, as well as those of most other countries in Europe, have yielded in considerable numbers the relics of Neolithic man. Dwellings constructed of piles were built in the water out of arrow-shot from the shore. Partly from destruction by fire, partly from successive reconstructions, the bottom of the water at these places is strewn with a thick accumulation of debris, from which vast numbers of relics of the old population have been recovered, revealing much of their mode of life.[1] Some of these settlements probably date far back beyond the beginning of the historic period. Others belong to the Bronze, and to the Iron Age. But the same site would no doubt be used for many generations, so that successive layers of relics of progressively later age would be deposited on the lake-bottom. It is believed that in some cases the lacustrine dwellings were still used in the first century of our era.

Denmark.—The shell-mounds (*Kjökken-mödding*), from three to ten feet high, and sometimes 1000 feet long, heaped up on various parts of the Danish coast-line, mark settlements of the Neolithic age. They are made up of refuse, chiefly shells of mussels, cockles, oysters, and periwinkles, mingled with bones of the herring, cod, eel, flounder, great auk, wild duck, goose, wild swan, capercailzie, stag, roe, wild boar, urus, lynx, wolf, wild cat, bear, seal, porpoise, dog, &c., with human tools of stone, bone, loam, or wood, fragments of rude pottery, charcoal, and cinders.

The Danish peat-mosses have likewise furnished relics of the early human races in that region. They are from 20 to 30 feet thick, the lower portion containing remains of Scotch fir (*Pinus sylvestris*) and Neolithic implements. This tree has never been indigenous in the country within the historic period. A higher layer of the peat contains remains of the common oak with bronze implements, while at the top come the beech tree and weapons of iron.

North America.—Prehistoric deposits are essentially the same on both sides of the Atlantic. In North America, as in Europe, no very definite lines can be drawn within which they should be confined. They cannot be sharply separated from the Champlain series on the one hand, nor from modern accumulations on the other. Besides the marshes, peat-bogs, and other organic deposits which belong to an early period in the human occupation of America, some of the younger alluvia of the river-valleys and lakes can no doubt claim a high antiquity, though they have not supplied the same copious evidence of early man which gives so much interest to the corresponding European formations. Heaps of shells of edible species, like those of Denmark, occur on the coasts of Nova Scotia, Maine, &c. The large mounds of artificial origin in the Mississippi valley have excited much attention. The early archæology of these regions has still to be explored.

[1] Keller's *Lake Dwellings of Switzerland.*

BOOK VII.

PHYSIOGRAPHICAL GEOLOGY.

An investigation of the geological history of a country involves two distinct lines of enquiry. We may first consider the nature and arrangement of the rocks that underlie the surface, with a view to ascertaining from them the successive changes in physical geography and in plant and animal life which they chronicle. But besides the story of the rocks we may try to trace that of the surface itself—the origin and vicissitudes of the mountains and plains, valleys and ravines, peaks, passes, and lake-basins which have been formed out of the rocks. The two enquiries traced backward merge into each other; but they become more and more distinct as they are pursued towards later times. It is obvious, for instance, that a mass of marine limestone which rises into groups of hills, trenched by river-gorges and traversed by valleys, presents two sharply contrasted pictures to the mind. Looked at from the side of its origin, the rock brings before us a sea-bottom over which the relics of generations of a luxuriant marine calcareous fauna accumulated. We may be able to trace every bed, to mark with precision its organic contents, and to establish the zoological succession of which these superimposed sea-bottoms are the records. But we may be quite unable to explain how such sea-formed limestone came to stand as it now does, here towering into hills and there sinking into valleys. The rocks and their contents form one subject of study; the history of their present scenery forms another.

The branch of geological enquiry which deals with the evolution of the existing contours of the dry land is termed Physiographical Geology. To be able to pursue it profitably, some acquaintance with all the other branches of the science is requisite. Hence its consideration has been reserved for this final division of the present work; but only a rapid summary can be attempted here.

At the outset one or two fundamental facts may be stated. It is evident that the materials of the greater part of the dry land have been laid down upon the floor of the sea. That they now not only rise above the sea-level, but sweep upwards into the crests of lofty mountains, can only be explained by displacement. Thus the land owes its existence mainly to upheaval of the terrestrial crust. The same sedimentary materials which demonstrate the fact of dis-

placement, afford an indication of its nature and amount. Having been laid down in wide sheets on the sea-bottom, they must have been originally, on the whole, level or at least only gently inclined. Any serious departure from this original position must therefore be the effect of displacement, so that stratification forms a kind of datum-line from which such effects may be measured.

Further, it is not less apparent that the sedimentary formations, besides having suffered from disturbance of the crust, have undergone extensive denudation. Even in tracts where they remain horizontal, they have been carved into wide valleys. Their detached outliers stand out upon the plains as memorials of what has been removed. Where on the other hand they have been thrown into inclined positions, the truncation of their strata at the surface points to the same universal degradation. Here again the lines of stratification may be used as datum-lines to measure approximately the amount of rock which has been worn away.

While, therefore, it is true that, taken as a whole, the dry land of the globe owes its existence to upheaval, it is not less true that its present contours are due mainly to erosion. These two antagonistic forms of geological energy have been at work from the earliest times, and the existing land with all its varied scenery is the result of their combined operation. Each has had its own characteristic task. Upheaval has, as it were, raised the rough block of marble, but erosion has carved that block into the graceful statue.

The very rocks of which the land is built up bear witness to this intimate co-operation of hypogene and epigene agency. The younger stratified formations have been to a large extent derived from the waste of the older, the same mineral ingredients being used over and over again. This could not have happened but for repeated uplifts whereby the sedimentary accumulations of the sea-floor were brought within reach of the denuding agents. Moreover, the internal characters of these formations point unmistakably to deposition in comparatively shallow water. Their abundant intercalations of fine and coarse materials, their constant variety of mineral composition, their sun-cracks, ripple-marks, rain-pittings, and worm-tracks, their numerous unconformabilities and traces of terrestrial surfaces, together with the prevalent facies of their organic contents, combine to demonstrate that the main mass of the sedimentary rocks of the earth's crust was accumulated close to land, and that no trace of really abysmal deposits is to be found among them. From these considerations we are led up to the conclusion that the present continental areas must have been terrestrial regions of the earth's surface from a remote geological period. Subject to repeated oscillations, so that one tract after another has disappeared and reappeared from beneath the sea, the continents, though constantly varying in shape and size, have yet maintained their individuality. We may infer likewise that the existing ocean basins have probably always been the great depressions of the earth's surface.

Geologists are now generally agreed that it is mainly to the effects of the secular contraction of our planet that the deformations and dislocations of the terrestrial crust are to be traced. The cool outer shell has sunk down upon the more rapidly contracting hot nucleus, and the enormous lateral compression thereby produced has thrown the crust into undulations, and even into the most complicated corrugations.[1] Hence in the places where the crust has yielded to the pressure it must have been thickened, being folded or pushed over itself, or being thrown into double bulges, one portion of which rises into the air, while the corresponding portion descends into the interior. Mr. Fisher contends that this downward bulging of the lighter materials of the crust into a heavier substratum underneath the great mountain-uplifts of the surface is indicated by the observed diminution in the normal rate of augmentation of earth-temperature beneath mountains,[2] and by the lessened deflection of the plumb-line in the same regions.

The close connection between upheaval and denudation on the one hand and depression and deposition on the other has often been remarked, and striking examples of it have been gathered from all parts of the world. It is a familiar fact that along the central and highest parts of a mountain chain, the oldest strata have been laid bare after the removal of an enormous thickness of later deposits. The same region still remains high ground, even after prolonged denudation. Again, in areas where thick accumulations of sedimentary material have taken place there has always been contemporaneous subsidence. So close and constant is this relationship as to have suggested the belief that denudation by unloading the crust allows it to rise, while deposition by loading it causes it to sink (*ante*, p. 287).[3]

It is evident that in the results of terrestrial contraction on the surface of the whole planet, subsidence must always have been in excess of upheaval, that in fact upheaval has only occurred locally over areas where portions of the crust have been ridged up by the enormous tangential thrust of adjacent subsiding regions. The tracts which have thus been as it were squeezed out under the strain of contraction have been weaker parts of the crust and have usually been made use of again and again during geological time. They form the terrestrial regions of the earth's surface. Thus, the continents as we now find them are the result of many successive uplifts, corresponding probably to concomitant depressions of the

[1] While these pages are passing through the press, the Rev. O. Fisher has published an able volume on the "Physics of the Earth's Crust," in which he endeavours to show that the secular contraction of a solid globe through mere cooling will not account for the observed phenomena; and he re-states his argument for the existence of a fluid substratum between the crust and the nucleus. See *ante*, p. 53.

[2] *Op. cit.* chap. xii. The rate observed in the Mont Cenis and Mont St. Gothard Tunnels was about 1° Fahr. for every 100 feet, or only about half the usual rate.

[3] This belief has in recent years been forcibly urged by American geologists who have studied the structure of the Western Territories. See especially the reports of Mr. Clarence King, Major Powell, and Captain Dutton.

ocean bed. In the long process of contraction the earth has not contracted uniformly and equably. There have been no doubt vast periods during which no appreciable or only excessively gradual movements took place; but there have probably also been intervals when the accumulated strain on the crust found relief in more or less rapid collapse.

The general result of such terrestrial disturbances has been to throw the crust of the earth into wave-like undulations. In some cases a wide area has been upheaved as a broad low arch with little disturbance of the original level stratification of its component rocks. More usually the undulations have been impressed as sensible deformations of the crust, varying in magnitude from the gentlest appreciable roll up to mountainous crests of complicated plication, inversion, and fracture. As a rule the undulations have been linear, but their direction has varied from time to time, having been determined at right angles, or approximately so, to the trend of the lateral pressure that produced them.

Considered with reference to their mode of production, the leading contours of a land-surface may be grouped as follows:—1. Those which are due more or less directly to disturbance of the crust. 2. Those which have been formed by volcanic action. 3. Those which are the result of denudation.

1. Terrestrial Features due more or less directly to Disturbance of the Crust.—In some regions large areas of stratified rocks have been raised up with so little trace of curvature that they seem to the eye to extend in horizontal sheets as wide plains or table-lands. If however these areas can be followed sufficiently far, the flat strata are eventually found to curve down slowly or rapidly, or to be truncated by dislocations. In an elevated region of this kind, the general level of the ground corresponds on the whole with the planes of stratification of the rocks. Vast regions of Western America, where Cretaceous and later strata extend in nearly horizontal sheets for many thousands of square miles at heights of 4000 feet or more above the sea, may be taken as illustrations of this structure.

As a rule, curvature is more or less distinctly traceable in every region of uplifted rocks. Various types of flexure may be noticed, of which the following are some of the more important.

(*a.*) *Monoclinal Flexures* (p. 516).—These occur most markedly in broad plateau regions and on the flanks of large broad uplifts, as in the table-lands of Utah, Wyoming, &c. They are frequently replaced by faults, of which indeed they may be regarded as an incipient stage (p. 526).

(*b.*) *Symmetrical Flexures*, where the strata are inclined on the two sides of the axis at the same or nearly the same angle, may be low gentle undulations or may increase in steepness till they become short sharp curves. Admirable illustrations of different degrees of inclination may be seen in the range of the Jura and the Appalachians, where the influence of this structure of the rocks on

external scenery may be instructively studied. In many instances each anticline forms a long ridge, and each syncline runs as a corresponding and parallel valley. It will usually be observed, however, that the surface of the ground does not strictly conform for more than a short distance to the surface of any one bed; but that, on the contrary, it passes across the edges of successive beds, as in Fig. 430. This relation—so striking a proof of the extent to which

Fig. 430.—Symmetrical Flexures of Suiss Jura.
(The ridges coinciding with anticlines and the valleys with synclines.)

the surface of the land has suffered from denudation—may be followed through successive phases until the original superficial contours are exactly reversed, the ridges running along the lines of syncline and the valleys along the lines of anticline (Figs. 337, 338). Among the older rocks of the earth's crust which have been exposed alike to curvature and prolonged denudation, this reversal may be considered to be the rule rather than the exception. We may suppose that the tension of curvature produced an actual rupture of the crest of an anticline along which the denuding agents might operate.

The *Uinta type* is a variety of this structure seen to great perfection in the Uinta Mountains of Wyoming and Utah. It consists of a broad flattened flexure from which the strata descend steeply or vertically into the low grounds, where they quickly resume their horizontality. In the Uinta Mountains the flat arch has a length of upwards of 150 and a breadth of about 50 miles, and exposes a vast deeply trenched plateau with an average height of 10,000 to

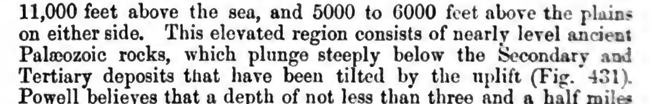

Fig. 431.—Uinta Type of Flexure.
a, Palæozoic rocks; *b*, Mesozoic; *c*, Tertiary; *f*, fault.

11,000 feet above the sea, and 5000 to 6000 feet above the plains on either side. This elevated region consists of nearly level ancient Palæozoic rocks, which plunge steeply below the Secondary and Tertiary deposits that have been tilted by the uplift (Fig. 431). Powell believes that a depth of not less than three and a half miles of strata has been removed by denudation from the top of the arch.[1] In some places the line of maximum flexure at the side of the uplift has given way, and the resulting fault has at one point a vertical displacement of 20,000 feet.

[1] *Geology of Uinta Mountains*, p. 201. There is in this work a suggestive discussion of types of mountain structure. See also Clarence King's *Report on Geology of 40th Parallel*, vol. i.

Another variety of more complex structure may be termed the *Park type*, from its singularly clear development in the Park region of Colorado. In this type an axis of ancient crystalline rocks—granites, gneisses, &c.—has been as it were pushed through the flexure, or the younger strata have been bent sharply over it so that after vast denudation their truncated ends stand up vertically along the flanks of the uplifted nucleus of older rocks (Fig. 432).

There may be only one dominant flexure, as in the case of the

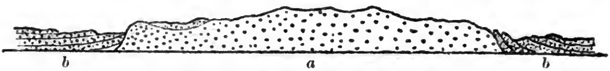

FIG. 432.—PARK TYPE OF FLEXURE.
a, Crystalline rocks; *b*, Mesozoic rocks.

Uinta Mountains, the long axial line of which is truncated at the ends by lines of flexure nearly at right angles to it. More usually numerous folds run approximately parallel to each other as in the Jura and Appalachian chains. Not infrequently some of them die out or coalesce. Their axes are seldom perfectly straight lines.

(*c.*) *Unsymmetrical Flexures*, where one side of the fold is much steeper than the other, but where they are still inclined in opposite directions, occur in tracts of considerable disturbance. The steep sides look away from the area of maximum disturbance, and are more sharply inclined as they approach it until the flexures become inverted. Instructive examples of this structure are presented by the Jura Mountains and the Appalachian chain. In these tracts it is observable that in proportion as the flexures increase in angle of inclination they become narrower and closer together, while, on the other hand, as they diminish into symmetrical forms, they become broader, flatter, and wider apart, till they disappear (Figs. 239, 433).

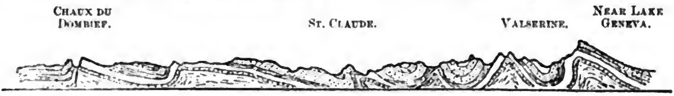

FIG. 433.—SECTION ACROSS WESTERN PART OF JURA MOUNTAINS.
(After P. Choffat, $\frac{1}{250000}$, A. Heim, *Mechanism. Gebirgsb.* Pl. xiii.)

(*d.*) *Reversed Flexures*, where the strata have been folded over in such a way that on both sides of the axis of curvature they dip in the same direction, occur chiefly in districts of the most intense plication, such as a great mountain chain like the Alps. The inclination, as before, is for the most part towards the region of maximum disturbance, and the flexures are often so rapid that after denudation of the tops of the arches the strata are isoclinal, or appear to be dipping all in the same direction (p. 518). A gradation can be traced through the three last-named kinds of flexure. The inverted or reversed type is found where the crumpling of the crust has been greatest. Away from the area of maximum disturbance the folds

pass into the unsymmetrical type, then with gradually lessening slopes into the symmetrical, finally widening out and flattening into the plains. If we bisect the flexures in a section of such a plicated region we find that the lines of bisection or "axis-planes" are vertical in the symmetrical folds, and gradually incline towards the more plicated ground at lessening angles.[1]

Fractures not infrequently occur along the axes of unsymmetrical and inverted flexures, the strata having snapped under the great tension, and one side (in the case of inverted flexures, usually the upper side) having been pushed over the other, sometimes with a vertical displacement of several thousand feet. It is along or parallel to the axes of plication, and therefore coincident with the general strike, that the great faults of a plicated region occur. As a rule dislocations are more easily traced among low grounds than among the mountains. One of the most remarkable and important faults in Europe, for example, is that which bounds the southern edge of the Belgian coal-field (p. 746). It can be traced across Belgium, has recently been detected in the Boulonnais, and may not improbably run beneath the Secondary and Tertiary rocks of the south of England. It is a remarkable fact that faults which have a vertical displacement of many thousands of feet produce little or no effect upon the surface. The great Belgian fault is crossed by the valleys of the Meuse and other northerly flowing streams. Yet so indistinctly is it marked in the Meuse valley that no one would suspect its existence from any peculiarity in the general form of the ground, and even an experienced geologist, until he had learned the structure of the district, would scarcely detect any fault at all.

(*e.*) *Alpine Type of Mountain Structure.*—It is along a great mountain chain like the Alps that the most colossal crumplings of the terrestrial crust are to be seen. In approaching such a chain one or more minor ridges may be observed running on the whole parallel with it, as the Jura ridges flank the north side of the Alps, and the sub-Himalayan ridges follow the southern base of the Himalayas. On the outer side of these ridges the strata may be flat or gently inclined. At first they undulate in broad gentle folds; but traced towards the mountains these folds become sharper and closer, their shorter sides fronting the plains, their longer slopes dipping in the opposite direction. This inward dip is often traceable along the flanks of the main chain of mountains, younger rocks seeming to underlie others of much older date. Along the north front of the Alps, for instance, the red molasse is overlaid by Eocene and older formations. The inversions increase in magnitude till they reach such colossal dimensions as the double fold of the Glärnisch, where Triassic, Jurassic, and Cretaceous rocks have been thrown over above the Eocene flysch and nummulitic limestone (p. 518). In such vast crumplings it may happen that portions of older strata are caught in the folds of later formations, and some care may be

[1] H. D. Rogers, *Trans. Roy. Soc. Edin.* xxi. p. 434.

required to discriminate the enclosure from the rocks of which it appears to form an integral and original part. Some of the recorded examples of fossils of an older zone occurring by themselves in a much younger group of plicated rocks may be thus accounted for.

The inward dip and consequent inversion traceable towards the centre of a mountain chain lead up to the fan-shaped structure (p. 519), where the oldest rocks of a series occupy the centre and overlie younger masses which plunge steeply under them. Classical examples of this structure occur in the Alps (Mont Blanc, St. Gothard), where crystalline rocks such as granite, gneiss, and schist, the oldest masses of the chain, have been ridged up into the central and highest peaks. Along these tracts denudation has been of course enormous, for the appearance of the granitic rocks at the surface has been brought about, not by actual extrusion into the air, but by prolonged erosion, which in these higher regions, where many forms of subaerial waste reach their most vigorous phase, has removed the vast overarching cover of younger rocks under which the crystalline nucleus lay buried.

With the crumpling and fracture of rocks in mountain-making, the hot springs must be connected, which so frequently rise along the flanks of a mountain chain. A further relation is to be traced between these movements and the opening of volcanic vents either along the chain or parallel to it, as in the Andes and other prominent ridges of the crust. Elevation, by diminishing the pressure on the parts beneath the upraised tracts, may permit them to assume a liquid condition and to rise within reach of the surface, when, driven upwards by the expansion of superheated vapours, they are ejected in the form of lava or ashes. Mr. Fisher supposes that the lower half of the double bulge of the crust in a mountain, by being depressed into a lower region, may be melted off, giving rise to siliceous lavas which rise before the deeper basaltic magma begins to be erupted.

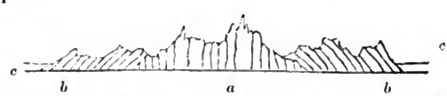

FIG. 434.—SECTION OF A MOUNTAIN CHAIN SHOWING TWO PERIODS OF UPHEAVAL.

A mountain chain may be the result of one movement, but probably in most cases is due to a long succession of such movements. Formed on a line of weakness in the crust, it has again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval. The successive stages of uplift are usually not difficult to trace. The chief guide is supplied by unconformability (p. 599). Let us suppose, for example, that a mountain range (Fig. 434) consists of upraised Lower Silurian rocks (*a*), upon the upturned and denuded edges of which the Carboniferous Limestone (*b b*) lies transgressively. The original upheaval of that range

must have taken place between the Lower Silurian and the Carboniferous Limestone periods. If, in following the range along its course, we find the Carboniferous Limestone also highly inclined and covered unconformably by the Upper Coal-measures (*c c*), we should know that a second uplift of that portion of the ground had taken place between the time of the Limestone and that of the Upper Coal-measures. Moreover, as the Coal-measures were laid down below the sea-level, a third uplift has subsequently occurred whereby they were raised into dry land. By this simple and obvious kind of evidence the relative ages of different mountain chains may be compared. In most great mountain chains, however, the rocks have been so intensely crumpled, and even inverted, that much labour may be required before their true relations can be determined.

The Alps offer an instructive example of a great mountain system formed by repeated movements during a long succession of geological periods. The central portions of the chain consist of gneiss, schists, granite, and other crystalline rocks, partly referable to the Archæan series, but some of which appear to be metamorphosed Palæozoic, Secondary, and even older Tertiary deposits. It would appear that the first outlines of the Alps were traced out even in Archæan times, and that after submergence, and the deposit of Palæozoic formations along their flanks, if not over most of their site, they were re-elevated into land. From the relations of the Mesozoic rocks to each other, we may infer that several renewed uplifts after successive denudations took place before the beginning of Tertiary times; but without any general and extensive plication. A large part of the range was certainly submerged during the Eocene period under the waters of that wide sea which spread across the centre of the Old World, and in which the nummulitic limestone and flysch were deposited. But after that period the grand upheaval took place to which the present magnitude of the mountains is chiefly due. The older Tertiary rocks, previously horizontal under the sea, were raised up into land, together with the older formations of the chain, and were crumpled, dislocated, and inverted. So intense was the compression to which the Eocene clays and sands were subjected that they were converted into hard and even somewhat crystalline rocks. It is strange to reflect that the enduring materials out of which so many of the mountains, cliffs, and pinnacles of the Alps have been formed are of no higher geological antiquity than the London clay and other soft Eocene deposits of the south of England. At a later stage of Tertiary time renewed disturbance led to the destruction of the lakes in which the molasse had accumulated, and their thick sediments were thrust up into large broken mountain masses, such as the Righi, Rossberg, and other prominent heights along the northern flank of the Alps. Since that great movement no paroxysm seems to have affected the Alpine region except the earthquakes, which from time to time show the process of mountain-making to be only suspended or still slowly in progress.

The gradual evolution of a continent during a long succession of geological periods has been admirably worked out for North America by Dana, Dawson, Dutton, Gilbert, Hayden, King, Newberry, Powell, and others. The general character of the structure is extreme simplicity, as compared with that of the Old World. In the Rocky Mountain region, for example, while the Palæozoic formations lie unconformably upon the Archæan gneiss, there is, according to King, a regular conformable sequence from the lowest Palæozoic to the Jurassic rocks. During the enormous interval of time represented by these massive formations what is now the axis of the continent remained undisturbed save by a gentle and protracted subsidence. In the great depression thus produced all the Palæozoic and a great part of the Mesozoic rocks were accumulated. At the close of the Jurassic period the first great upheavals took place. Two lofty ranges of mountains,—the Sierra Nevada (now with summits more than 14,000 feet high) and the Wahsatch,—400 miles apart, were pushed up from the great subsiding area. These movements were followed by a prolonged subsidence, during which Cretaceous sediments accumulated over the Rocky Mountain region to a depth of 9000 feet or more. Then came another vast uplift, whereby the Cretaceous sediments were elevated into the crests of the mountains, and a parallel coast-range was formed fronting the Pacific. Intense metamorphism of the Cretaceous rocks is stated to have taken place. The Rocky Mountains, with the elevated table-land from which they rise, now permanently raised above the sea, were gradually elevated to their present height. Vast lakes existed among them, in which, as in the Tertiary basins of the Alps, enormous masses of sediment accumulated. The slopes of the land were clothed with an abundant vegetation, in which we may trace the ancestors of many of the living trees of North America. One of the most striking features in the later phases of this history was the outpouring of great floods of trachyte, basalt, and other lavas from many points and fissures over a vast space of the Rocky Mountains and the tracts lying to the west. In the Snake River region alone the basalts have a depth of 700 to 1000 feet, over an area 300 miles in breadth.

These examples show that the elevation of mountains, like that of continents, has been occasional, and, so to speak, paroxysmal. Long intervals elapsed when a slow subsidence took place, but at last a point was reached when the descending crust, unable any longer to withstand the accumulated lateral pressure, was forced to find relief by rising into mountain ridges. With this effort the elevatory movements ceased. They were followed either by a stationary period, or more usually by a renewal of the gradual depression, until eventually relief was again obtained by upheaval, sometimes along new lines, but often on those which had previously been used. The intricate crumpling and gigantic inversions of a great mountain chain naturally suggest that the movements which caused these disturbances of the strata were sudden and violent. And this inference

may in most cases be correct. It is not so easy, however, to demonstrate that a disturbance was rapid as to prove that it must have been slow. That some uplifts resulting in the rise of important mountain ranges have been almost insensibly brought about, can be shown from the operation of rivers in the regions affected. Thus the rise of the Uinta Mountains has been so quiet, that the Green River, which flowed across the site of the range, has not been deflected, but has actually been able to deepen its cañon as fast as the mountains have been pushed upward.[1] The Pliocene accumulations along the southern flanks of the Himalayas show that the rivers still run in the same lines as they occupied before the last gigantic upheaval of the chain (p. 879).

2. Terrestrial Features due to Volcanic Action.—The two types of volcanic eruptions described in Book III. Part I., give rise to two very distinct types of scenery. The ordinary volcanic vent leads to the piling up of a conical mass of erupted materials round the orifice. In its simplest form the cone is of small size and has been formed by the discharges from a single funnel, like many of the tuff and cinder cones of Auvergne, the Eifel, and the Bay of Naples. Every degree of divergence from this simplicity may be traced, however, till we reach a colossal mountain like Etna, wherein, though the conical form is still retained, eruptions have proceeded from so many lateral vents that the main cone is loaded with minor volcanic hills. Denudation as well as explosion comes into play; deep and wide valleys, worn down the slopes, serve as channels for successive floods of lava or of water and volcanic mud. On the other hand the type of fissure-eruption in which the lava, instead of issuing from a central vent, has welled upward from many parallel or connected fissures, leads to the formation of wide lava-plains composed of successive level sheets of lava. By subsequent denudation these plains are trenched by valleys, and along their margin are cut into escarpments with isolated blocks or outliers. They thus become great plateaux or table-lands like those of north-west Europe, the Deccan, and Abyssinia (pp. 256, 565).

The forms assumed by volcanic masses of older Tertiary and still earlier geological date are in the main due not to their original contours, but to denudation. The rocks, being commonly harder than those among which they lie, stand out prominently, and often, in course of time and in virtue of their mode of weathering, assume a conical form, which, however, has obviously no relation to that of the original volcano. Eminences formed after the type of the Henry Mountain (p. 546) owe their dome-shape to the subterranean effusion of erupted lava, but the superficial irregularities of contour in the domes must be ascribed to denudation.

[1] Powell's *Geology of the Uinta Mountains*, in the Reports of *U. S. Geographical and Geological Survey, Rocky Mountain Region*, 1876. The same conclusion is drawn by Gilbert from the structure of the Wahsatch Mountains. See his admirable essay on "Land Sculpture," in his *Geology of the Henry Mountains*, published in same series of Reports, 1877.

3. Terrestrial Features due to Denudation.—The general results of denudation have been discussed in Book III. Part II. sect. ii. Every portion of the land, as soon as it rises above the sea-level, is attacked by denuding agents. Hence the older a terrestrial surface the more may it be expected to show the results of the operation of these agents. We have already seen how comparatively rapid are the processes of subaerial waste (p. 444). It is accordingly evident that the present contours of the land cannot be expected to reveal any trace whatever of the early terrestrial surfaces of the globe. The most recent mountain chains and volcanoes may, indeed, retain more or less markedly their original superficial outlines; but these must be more and and more effaced in proportion to their geological antiquity.

The fundamental law in the erosion of the terrestrial surfaces is that harder rocks resist decay more, while softer rocks resist it less. The former consequently are left projecting, while the latter are worn down. The terms "hard" and "soft" are used here in the sense of being less easily and more easily abraded, though every rock suffers in some measure. If, therefore, a perfectly level surface, composed of rocks exceedingly unequal in power of resistance, were to be raised above the sea, and to be exposed to the action of weathering, it would eventually be carved into a system of ridges and valleys. The eminences would be determined by the position of the harder rocks, the depressions by the site of the softer. Every region of Mesozoic or Palæozoic rocks affords ample illustration of this result. The hills and prominent ridges are found to be where they are, not because they have been specially upheaved, but because they are composed of more durable materials, or because by the disposition of the original drainage lines they have been less eroded than the valleys.

In this marvellous process of land-sculpture we have to consider on the one hand the agents and combinations of agents which are at work, and on the other the varying powers of resistance arising from declivity, composition, and structure of the materials on which these agents act. The forces or conditions required in denudation—air, aridity, rain, springs, frost, rivers, glaciers, the sea, plant and animal life—have been described in Book III. Part II. Every country and climate must obviously have its own combination of erosive activities. The decay of the surface in Egypt or Arizona arises from a different group of forces from that which can be seen in the west of Europe or in New England.

In tracing the sculpture of the land we are soon led to perceive the powerful influence of the angle of slope of the ground upon the rate of erosion. This rate decreases as the angle lessens, till on level plains it reaches its minimum. Other things being equal a steep mountain ridge will be more deeply eroded than one of the same elevation which rises gradually out of the plains. Hence the declivity of the ground at its first elevation into land must have had an important bearing upon the subsequent erosion of the

slopes. It is important to observe that the depressions into which the first rain gathered on the surface of the newly upraised land would in most cases become the permanent lines of drainage. They would be continually deepened as the water coursed in them, so that unless where subterranean disturbance came into play, or where the channels were obstructed by landslips or otherwise, the streams would be unable to quit the channels they had once chosen. The permanence of drainage-lines is one of the most remarkable features in the geological history of the continents. The main valleys of a country are usually among the oldest parts of its topography. As they are widened and deepened the ground between them may be left projecting into high ridges and even prominent isolated hills.

A chief element in the progress of land-sculpture is geological structure—the character, arrangement, and composition of the rocks and the manner in which each variety yields to the attacks of the denuding agents. Besides the general relations of the so-called hard rocks to resulting prominences, and of soft rocks to depressions, the broader geotectonic characters have had a dominant influence upon the evolution of terrestrial contours. As illustrations of this influence, reference may be made to the marked difference between the scenery of districts composed of stratified sedimentary rocks, and that of areas of massive eruptive rocks such as granite. In the former case, bedding and joints furnish divisional lines, the guiding influence of which upon the external forms of the mountains is everywhere traceable. In the case of eruptive masses the rock is split open along joints only, which mainly determine the shapes of crest, cliff, and corry.

Bedding produces a distinct type of scenery which can be traced from the sides of a mere brook up into tall sea-cliffs or into lofty mountain groups. Moreover, much of the ultimate character of the scenery depends upon whether the strata have been left undisturbed; for the position of the bedding, whether flat, inclined, vertical, or contorted, largely determines the nature of the surface. The most characteristic scenery formed by stratified rocks is undoubtedly where the bedding is horizontal, or nearly so, and the strata are massive. A mountain constructed of such materials appears as a colossal pyramid, the level lines of stratification looking like gigantic courses of masonry. Joints and faults traversing the bedding allow it to be cleft into blocks and deep chasms that heighten the resemblance to ruined architecture. Probably the most marvellous illustrations of these results are to be found in the Western Territories of the United States. The vast table-lands of Colorado in particular offer a singularly impressive picture of the effects of mere subaerial erosion on undisturbed and nearly level strata (see frontispiece). Systems of stream-courses and valleys, river gorges, unexampled elsewhere in the world for depth and length, vast winding lines of escarpment, like ranges of sea-cliffs, terraced slopes rising from plateau to plateau, huge buttresses and

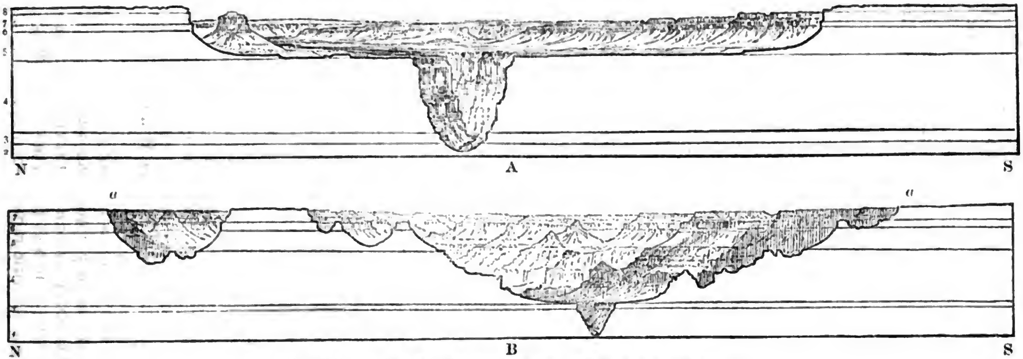

Fig. 435.—Sections across the Grand Cañon of the Colorado.[1]
(Vertical and Horizontal Scale the same.)
A. Section in the Kanab division. B. Section in the Kaibab division. *a* to *a* seven miles.

		Thickness in A.	Thickness in B.
Permo-Carboniferous	8. Bellerophon beds	250 ft.	——
Coal-measures	7. Cherty Limestone	350 ,,	500 ft.
	6. Cross-bedded Sandstone	200 ,,	400 ,,
	5. Aubrey red Shales, &c.	1200 ,,	900 ,,
Lower Carboniferous	4. Red Wall	2500 ,,	2200 ,,
	3. Tonto group	300 ,,	200 ,,
	2. Silurian rocks (covered unconformably by overlying rocks)	300 ,,	——
	1. Granite, Schist, &c., eroded before deposition of Carboniferous rocks	——	1200 ,,

[1] Drawn on a true scale for this work by Mr. Holmes, whose diagrams of the geological structure and scenery of Western America are probably at once the most artistic and instructive sketches with which geological literature has yet been enriched. To his graphic pencil also the author owes the frontispiece to this volume.

solitary stacks standing like islands out of the plains, great mountain masses towering into picturesque peaks and pinnacles, cleft by innumerable gullies, yet everywhere marked by the parallel bars of the horizontal strata out of which they have been carved—these are the orderly symmetrical characteristics of a country where the scenery is due entirely to the action of subaerial agents and the varying resistance of level or little disturbed stratified rocks.

On the other hand where stratified rocks have been subjected to plications and fractures, their characteristic features may be gradually almost lost among those of the crystalline masses which under these circumstances are so often found to have been forced through them. The Alps may be cited as a well-known example of this kind of scenery. The whole geological aspect of these mountains is suggestive of former intense commotion. Yet on every side are to be seen proofs of the most enormous denudation. Twisted and crumpled, the solid sheets of limestone may be seen as it were to writhe from the base to the summit of a mountain, yet they present everywhere their truncated ends to the air, and from these ends it is easy to see that a vast amount of material has been worn away. Apart altogether from what may have been the shape of the ground immediately after the upheaval of the chain, there is evidence on every side of gigantic denudation. The subaerial forces that have been at work upon the Alpine surface ever since it first appeared have dug out the valleys, sometimes acting in original depressions, sometimes eroding hollows down the slopes. Moreover they have planed down the flexures, excavated lake-basins, scarped the mountain sides into cliff and *cirque*, notched and furrowed the ridges, splintered the crests into chasm and *aiguille*, until no part of the original surface now remains in sight. And thus the Alps remain a marvellous monument of stupendous earth-throes followed by a prolonged and gigantic denudation.

In massive rocks the structure-lines are those of joints alone, and according to the direction of the intersecting joints the trend and shape of the ridges are determined. The importance of rock-joints, not only in details of scenery, but even in some of the main features of the mountain outlines of massive rocks, is hardly at first credible. Yet it is along these divisional lines that the rain has filtered, and the springs have risen, and the frost wedges have been driven. On the bare scarps of a high mountain where the inner structure of the mass is laid open, the system of joints is seen to have determined the lines of crest, the vertical walls of cliff and precipice, the forms of buttress and recess, the position of cleft and chasm, the outline of spire and pinnacle. On the lower slopes, even under the tapestry of verdure which nature delights to hang where she can over her naked rocks, we may detect the same pervading influence of the joints upon the forms assumed by ravines and crags. Each kind of eruptive rock has its system of joints, and these in large measure determine its own characteristic form of scenery.

A few of the more important features of the land may be briefly noticed here in their relation to this branch of geology. In the physiography of any region, mountains are the dominant features (p. 37). A true mountain chain consists of rocks that have been crumpled and pushed up in the manner already described. But ranges of hills almost mountainous in their bulk may be formed by the gradual erosion of valleys out of a mass of original high ground. In this way some ancient table-lands have been so channelled that they now consist of massive rugged hills, either isolated or connected along the flanks. Eminences detached by erosion from the masses of rock whereof they once formed a part, have been termed *hills of circumdenudation.* Their isolation may either be due to the action of streams working round them, apart altogether from geological structure, or to their more resisting constitution, which has enabled them to remain prominent during the general degradation of the whole surface.

Table-lands (p. 40) may sometimes arise from the abrasion of hard rocks and the production of a level plain by the action of the sea, or rather of that action combined with the previous degradation of the land by subaerial waste (p. 451). Such a form of surface may be termed a *Table-land of Denudation.* Notable examples are to be seen in the extensive "fjelds" or elevated plateaux of Scandinavia, many of which, rising above the snow-line, form the gathering ground for the glaciers that descend almost to the sea-level. Fragments of a similar table-land may be recognized among the Grampian Mountains of Scotland. But most of the great table-lands of the globe seem to be platforms of little-disturbed strata, either sedimentary or volcanic, which have been upraised bodily to a considerable elevation. These may be termed *Table-lands of Deposit.* But whatsoever its mode of origin, the plateau undergoes a gradual transformation under continued denudation. No sooner are the rocks raised above the sea than they are attacked by running water, and begin to be hollowed out into systems of valleys. As the valleys sink, the platforms between them grow into narrower and more definite ridges, until eventually the level table-land is converted into a complicated network of hills and valleys, wherein, nevertheless, the key to the whole arrangement is furnished by a knowledge of the disposition and effects of the flow of water. The examples of this process brought to light in Colorado, Wyoming, Nevada, and the other western Territories, by Newberry, King, Hayden, Powell, Gilbert, Dutton, and other explorers, are among the most striking monuments of geological operations in the world. The erosion of the ancient table-lands of Scandinavia and Scotland, and their conversion into systems of hilly ridges and valleys, convey less impressive but still instructive complete evidence of the efficacy of subaerial waste.

Watersheds are of course at first determined by the form of the earliest terrestrial surface. But they are less permanent than the

watercourses that diverge from them. Where a watershed lies symmetrically along the centre of a country or continent with on either side an equal declivity and rainfall, and an identity of geological structure, it will be permanent, because the erosion on each slope proceeds at the same rate. But such a combination of circumstances can happen rarely, save on a small and local scale. As a rule watersheds lie on one side of the centre of a country or continent, and the declivity is steeper on the side nearest the sea. Hence, apart from any influence from difference of geological structure, the tendency of erosion, by wearing the steep slope more than the gentle one, is to carry the watershed backward nearer to the true centre of the region, especially at the heads of valleys. Of course this is an extremely slow process; but it must be admitted to be one of real efficacy in the vast periods during which denudation has continued. Excellent illustration of its progress, as well as of many other features of land-sculpture, may often be instructively studied on clay banks exposed to the influence of rain.[1]

The crests of mountains are watersheds of the sharpest type where erosion has worked backward upon a steep slope on either side. Their forms are mainly dependent upon structure, and especially upon systems of joints. It will often be observed that the general trend of a crest coincides with that of one set of joints, and that the bastions, recesses, and peaks have been determined by the intersection of another set. If the rock is uniform in structure and the declivity equal in angle on either side, a crest may retain its position, but as one side is usually considerably steeper than the other, the crest advances at the expense of the top of the gentler declivity. But under any circumstances it is continually lowered in level, for it may be regarded as the part of a mountain where the rate of subaerial denudation reaches a maximum. An ordinary cliff is attacked only in front, but a crest has two fronts and is further splintered along its summit. Nowhere can the guiding influence of geological structure be more conspicuously seen than in the array of spires, buttresses, gullies, and other striking outlines which a mountain crest assumes.

Valleys are mainly due to erosion, guided either by original depressions of the ground, or by geological structure, or by both. Their contours depend partly on the structure and composition of the rocks, and partly on the relative potency of the different denuding agents. Where the influence of air, rain, frost, and general subaerial weathering has been slight, and the streams, supplied from distant sources, have had sufficient declivity, deep, narrow, precipitous ravines or gorges have been excavated. The cañons of the Colorado are a magnificent example of this result (Fig. 435). Where, on the other hand, ordinary atmospheric action has been more rapid, the sides of the river channels have been attacked, and open sloping glens and

[1] See on this subject Mr. Gilbert's suggestive remarks in the essay on "Land-sculpture" already cited (p. 920).

valleys have been hollowed out. A gorge or defile is usually due to the action of a waterfall, which, beginning with some abrupt declivity or precipice in the course of the river when it first commenced to flow, or caused by some hard rock crossing the channel, has eaten its way backward, as already explained (p. 375).

A pass is a portion of a watershed which has been cut down by the erosion of two valleys, the heads of which adjoin on opposite sides of a ridge. Each valley is cut backward until the intervening ridge is demolished. Most passes no doubt lie in original but subsequently deepened depressions between adjoining mountains. The continued degradation of a crest may obviously give rise to a pass.

Lakes may have been formed in several ways. 1. By subterranean movements, as, for example, in mountain-making and in volcanic explosions. The subsidence of the central part of a mountain system might conceivably depress the heads of the valleys below the level of portions further from the sources of the streams. Or the elevation of the lower parts of the valleys might cause an accumulation of water in their upper parts. Or each lake-basin might be supposed to be due to a special subsidence. But these hollows, unless continually deepened by subsequent movements of a similar nature, would be filled up by the sediment continually washed into them from the adjoining slopes. The numerous lakes in such a mountain system as the Alps cannot be due merely to subterranean movements, unless we suppose the upheaval of the mountains to have been quite recent, or that subsidence must take place continuously or periodically below each independent basin. But there is evidence that the Alpine uplift is not of such recent date, while the idea of perpetuating lakes by continued local subsidence would demand, not in the Alps merely, but all over the northern hemisphere, where lakes are so abundant, an amount of subterranean movement of which, if it really existed, there would assuredly be plenty of other evidence. 2. By irregularities in the deposition of superficial accumulations prior to the elevation of the land, or, in the northern parts of Europe and America, during the disappearance of the ice-sheet. The numerous tarns and lakes enclosed within mounds and ridges of drift-clay and gravel are examples. 3. By the accumulation of a barrier across the channel of a stream and the consequent ponding back of the water. This may be done, for instance, by a landslip, by a lava stream, by the advance of a glacier across a valley, or by the throwing up of a bank by the sea across the mouth of a river. 4. By erosion. The only agent capable of excavating hollows out of the solid rock such as might form lake-basins is glacier-ice (p. 416). It is a remarkable fact, of which the significance may now be seen, that the innumerable lake basins of the northern hemisphere lie on surfaces of intensely ice-worn rock. The striæ can be seen on the smoother rock-surfaces slipping into the water on all sides. These striæ were produced by ice moving over the rock. If the ice could, as the striæ prove, descend into the

rock-basins and mount up the farther side, smoothing and striating the rock as it went, it could, to a certain depth at least, erode basins.

In the general subaerial denudation of a country, innumerable minor features are worked out as the structure of the rocks controls the operations of the eroding agents. Thus, among undisturbed or gently inclined strata, a hard bed resting upon others of a softer kind is apt to form along its outcrop a line of cliff or escarpment. Though a long range of such cliffs resembles a coast that has been worn by the sea, it may be entirely due to mere atmospheric waste. Again, the more resisting portions of a rock may be seen projecting as crags or knolls. An igneous mass will stand out as a bold hill from amidst the more decomposable strata through which it has risen. These features, often so marked on the lower grounds, attain their most conspicuous development among the higher and barer parts of the mountains, where subaerial disintegration is most rapid. The torrents tear out deep gullies from the sides of the declivities. Corries or cirques, if not originally scooped out by converging streamlets (their mode of formation is a somewhat difficult problem), are at least enlarged by this action, and their naked precipices are kept bare and steep by the wedging off of successive slices of rock along lines of joint. Harder bands of rock project as massive ribs down the slopes, shoot up into prominent peaks, or, with the combined influence of joints and faults, give to the summits the notched saw-like outlines they so often present.

The materials worn from the surface of the higher are spread out over the lower grounds. We have already traced how streams at once begin to drop their freight of sediment when, by the lessening of their declivity, their carrying power is diminished (pp. 367, 382). The great plains of the earth's surface are due to this deposit of gravel, sand, and loam. They are thus monuments at once of the destructive and reproductive processes which have been in progress unceasingly since the first land rose above the sea and the first shower of rain fell. Every pebble and particle of the soil of the plains, once a portion of the distant mountains, has travelled slowly and fitfully downward. Again and again have these materials been shifted, ever moving seaward. For centuries, perhaps, they have taken their share in the fertility of the plains and have ministered to the nurture of flower and tree, of the bird of the air, the beast of the field, and of man himself. But their destiny is still the great ocean. In that bourne alone can they find undisturbed repose, and there, slowly accumulating in massive beds, they will remain until, in the course of ages, renewed upheaval shall raise them into future land, and thereby enable them once more to pass through a similar cycle of change.

THE END.

LIST OF AUTHORS QUOTED OR REFERRED TO.

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